TOUCH SCREEN TABLETS TOUCHING CHILDREN'S LIVES

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PUBLISHED IN: Frontiers in Psychology

frontiers Research Topics

frontiers

ISSN 1664-8714
ISBN 978-2-88945-417-4
DOI 10.3389/978-2-88945-417-4

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TOUCH SCREEN TABLETS TOUCHING CHILDREN'S LIVES

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Citation: Tarasuik, J., Strouse, G., Kaufman, J., eds. (2018). Touch Screen Tablets Touching Children's Lives. Lausanne: Frontiers Media. doi: 10.3389/978-2-88945-417-4

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frontiers in Psychology

ORIGINAL RESEARCH
published: 20 September 2017
doi: 10.3389/fpsyg.2017.01586

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Transfer of Problem Solving Skills from Touchscreen to 3D Model by 3- to 6-Year-Olds

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Although much published research purports that young children struggle to solve problems from screen-based media and to transfer learning from a virtual to a physical modality, Huber et al. (2016)'s recent study on children solving the Tower of Hanoi (ToH) problem on a touchscreen app offers a clear counter example. Huber et al. (2016) reported that children transferred learning from media to the physical world. As this finding arguably differs from that of prior research in this area, the current study tests whether the Huber et al. (2016) results could be replicated. Additionally, we extended the scope of the Huber et al. (2016) work by testing a broader age range, including children as young as 3 years, and using a culturally distinct participant pool. The results of the current study verified Huber et al.'s (2016) conclusion that 4- to 6-year-old children are capable of transferring the ToH learning from touchscreen devices to the physical version of the puzzle. Children under 4 years of age, in contrast, showed little ability to improve at the ToH problem regardless of the practice modality—suggesting that a different problem-solving task is required to probe very young children's ability to learn from touchscreen apps.

Keywords: children, multimedia, touchscreen, human–computer interaction, transfer of learning

OPEN ACCESS

Edited by:
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Specialty section:
This article was submitted to Developmental Psychology, a section of the journal Frontiers in Psychology

Received: *12 March 2017*
Accepted: *30 August 2017*
Published: *20 September 2017*

Citation:
Tarasuik J, Demaria A and Kaufman J (2017) Transfer of Problem Solving Skills from Touchscreen to 3D Model by 3- to 6-Year-Olds. Front. Psychol. 8:1586. doi: 10.3389/fpsyg.2017.01586

INTRODUCTION

Touch screen devices such as tablet, computers, and smart phones provide adults and children with access to countless interactive apps, many of which claim to offer learning opportunities (Shuler, 2012). These claims, however, run counter to the literature underlying most media use guidelines published by government bodies and academic and medical organizations. Most published research suggests that while young children may learn a skill or problem-solving strategy from screen-based media, they struggle to apply this learning in a new non-screen-based context (Hirsh-Pasek et al., 2015).

For example, Zack et al. (2009, 2013) conducted button-pressing imitation experiments with 15-month-old children. In these experiments, an adult demonstrated a button-press with either a real physical button (3D modality or simply "3D") or a virtual button presented on a touchscreen display (2D modality or simply "2D"). Examining whether children would imitate this action within and across modalities, Zack et al. (2009, 2013) reported that children were most likely to imitate an adult's demonstrated action when the adult and child performed their actions in the same modality, i.e., children observe on a 2D screen and imitate on a 2D screen (2D-2D) or children observe on 3D object and imitate on the 3D object (3D-3D). In contrast, imitation was significantly impaired when the observation and imitation modalities differed (3D-2D and 2D-3D). Zack et al. (2009, 2013) concluded that although imitation skill can be learned in either modality, the imitation skill cannot effectively be transferred across modalities.

Similarly, using an imitation paradigm involving a puzzle assembly task, Moser et al. (2015) demonstrated a similar finding with 2.5- and 3-year-old children. Results revealed a transfer deficit (i.e., a drop in performance across modalities) when the children were required to imitate on the touch screen device what they observed on the felt board puzzle (3D-2D) and vice versa (2D-3D) compared to imitation that did not require a transfer across modalities. Interestingly, however, not all researchers find transfer deficits in their experiments. Chen and Siegler (2013) found that children as young as 2 years of age could learn to imitate a series of steps to solve a spatial problem using tools from a video presentation—therefore not showing the transfer deficit seen in the imitation studies described above. Chen and Siegler (2013) highlight that 2D content that conveys that there is a problem to be solved can be challenging for young children, and learning from video is increasingly difficult as the number of steps required to achieve a goal increases (Barr, 2010; Barnett, 2014). Furthermore, learning to solve problems is increasingly reliant upon engagement in the task as the task complexity increases (e.g., Bauer and Mandler, 1992).

In light of these potentially contradictory findings, Huber et al. (2016) (the reference study here), examined the extent to which a change in modality affected children's learning of a problem-solving task. In that study, it was hypothesized that children would show significant transfer of learning from a 2D to 3D modality because solving the task requires engagement in the process, potentially overriding focus on superficial modality-based differences. Most initiation studies in contrast, require nothing during the "learning" phase apart from observation. Therefore, it is possible that children show a transfer deficit either because they are not sufficiently engaged in the learning process or that they find it easiest to imitate under conditions that are superficially similar to those seen during the demonstration.

Huber et al. (2016) examined 4- to 6-year-old children's ability to transfer learning acquired while solving a Tower of Hanoi (ToH) problem on a touchscreen device to solving the standard physical version of the problem. The results were that, regardless of the modality in which a child practiced, children's performance on the task improved significantly after practice. Indeed, there was no evidence that practicing on the physical version conferred any advantages over practicing with the 2D version as measured by final performance on a physical version test trial. These results suggest that children are able to transfer what they have learned from a touchscreen to "real-world" situation. Huber et al.'s (2016) finding stands out because transfer of problem solving skills from screen media 2D modality to the physical context of 3D modality is often claimed to be particularly difficult for young children (e.g., Schmidt and Vandewater, 2008). This raises the importance of replicating the Huber study to confirm its validity to our understanding of children's learning from touchscreen media.

As such, the current investigation aimed to replicate the findings of Huber et al. (2016) (also referred to here as the "reference" study), hypothesizing comparable patterns of results for analyses including participants of the same age. Additionally, as the majority of the previous work has investigated children younger than the 4- to 6-years-olds studied in the reference study, the current study expanded the reference study's age range to include younger children (from 3 years of age). Historically, studies of computer use have not examined children under 4 years because traditional desktop computer use requires cognitive and motor skills unavailable to younger children. However, with the rise of tablets, children are using computing devices as early as a child's first year of life (Kabali et al., 2015; Tarasuik and Kaufman, 2017) which is reflected in the wide range of "educational" apps targeting parents of young children (Hirsh-Pasek et al., 2015). Our inclusion of this younger group aims to help fill this newly relevant gap.

Based findings of Chen and Siegler (2013), it was hypothesized that the younger children would also demonstrate transfer, provided that they could sufficiently improve at the problem-solving task over multiple trials in any modality. Also, the transfer of learning protocol used by Huber et al. (2016) in Australia was replicated in Croatia, using the same materials developed by Huber and colleague's research team and the same physical materials and software (but with a different set of experimenters). Conditions replicated the reference study absent the condition where participants completed the task solely with the physical model, as the focus of the research was transferring learning across modalities.

MATERIALS AND METHODS

This experiment was designed to determine how experience with a problem-solving task in a particular modality (i.e., using physical "3D" vs. virtual "2D") affects children's improvement in performance in a new modality. The procedure for the current study largely replicates that used in Huber et al. (2016) in which children completed four trials on a three disk ToH puzzle. Specifically, the methods were designed to answer the questions: How does practice with a virtual puzzle transfer to performance with the traditional, physical puzzle?

Participants

A total of 49 children (45% male) aged 3.1 to 6.5 years ($M = 4.8$, $SD = 1.1$) were included in the analysis. An additional six children participated but were excluded from analysis due to failure to follow instructions on any trial ($n = 1$) or failure to complete all l four trials in the experiment ($n = 5$). Croatian was the main language spoken by all children, although some attended English ($n = 11$) or Italian ($n = 11$) language classes, and none of the children were reported to have any additional health care needs. More than half of mothers and almost a third of father had completed a minimum of an undergraduate university qualification, and family income (in Croatian Kuna) was reported to be <kn50K with exception of one family whose reported income was kn75K < kn100K. The participants were recruited from a day care centre in Rijeka, a metropolitan city of Croatia.

Materials

The experiment used the ToH problem solving puzzle, selected because of its extensive use with children as an assessment of problem solving, planning ability and executive functioning (Huber et al., 2016).

The experiment used the three-peg, three-disk version of the ToH puzzle. The 3D version was a traditional, timber incarnation of the ToH which consisted of natural wooden-looking pegs; and three wooden disks, each a different color and size (small, medium, and large). The 2D version of the ToH task was performed on a commercially available, iPad application ("Extra Tower of Hanoi" by Morard Dany).

To solve the ToH puzzle the child must move all three disks to one specific peg, while abiding by three rules: (1) only one disk can be moved at a time, (2) a disk cannot be placed on a smaller disk, and (3) the disks can only be placed on one of the three pegs (i.e., they cannot be put on the ground or table). **Figure 1** shows the initial state and the target state for the pegs.

Each child attempted to solve the ToH puzzle four times, as described below in the Procedure section. During each of those four trials, the child had a ToH set (or iPad running a ToH app) in front of them, while another set (2D or 3D as appropriate) depicting the goal state, sat across the table (in front of the experimenter) for the child to reference any time during the task.

Consistent with the reference study, we used the "monkey family" variation of instructions, based on Klahr (1978). The experimenter told the child that the disks were a family of monkeys: a father monkey (large disk), a mother monkey (medium-sized disk) and a baby monkey (small disk). The monkeys were described as "tired" so the task was to move them to their sleeping tree—the peg furthest to the child's right. It was explained that only one monkey could leave the tree at time, and a bigger monkey could not sit on a smaller monkey. The instructions were provided in Croatian, the language in which the experimenter and participants communicated. Participants were continuously recorded using an unobtrusively placed camera.

Procedure

Our procedure was the same as that used by Huber et al. (2016), with the exception that, for all children, the initial state of the puzzle was set up with the first two moves pre-completed (see **Figure 1** above) such that it could be optimally solved in five moves (with each extra move indicating less optimal performance). This varied slightly from the reference study, in which children were assigned to either a 5-move or 7-move version of the puzzle depending on how they performed on a pretest probe trial. In the current study, we focused on the 5-move version because our participant pool included younger children who were very unlikely to succeed at the 7-move version even after extended practice.

We randomly assigned each child to one of three experimental conditions as follows:

- In the first condition, 3D-3D-3D-3D (or "No-transfer Condition") we had the children attempt the task on the physical, 3D version of the puzzle on all four trials. This condition served as a baseline to demonstrate how children generally perform when no transfer of knowledge across modality is necessary ($n = 17$, age: $M = 4.7$, $SD = 1.1$).

- In the second condition, 3D-2D-2D-3D (or "Transfer Condition"), we had the children attempt the 3D trial initially, followed by two trials using the 2D version (i.e., with the ToH iPad app), and finally use the 3D version in the last trial. By comparing children in this condition to those in the 3D-3D-3D-3D condition, we probe the extent, if at all, practicing in the virtual modality affects performance afterwards in the 3D modality ($n = 16$, age: $M = 4.9$, $SD = 1.2$).

- The third condition, 2D-2D-2D-3D (or "No Pre-exposure Condition") is similar to the 3D-2D-2D-3D condition, except that children were never exposed during the study to the 3D version until the final trial. This condition is included to ascertain if pre-exposure to the 3D version is necessary for children to effectively learn from the 2D version and/or apply learning in the 2D version back to the 3D version ($n = 16$, age: $M = 4.8$, $SD = 1.2$).

The protocol was approved by ethics board at University of Rijeka and undertaken conforming to the regulations. All children who participated did so with the written informed consent of at least one parent or guardian.

Coding and Analyses

From the video and screen recordings we coded all disk moves in each of the four trials for each child. For each trial, for each child, we calculated the time to complete the task and the number of moves used to complete the test. In trials where the children solved the puzzle within the given 5-min period, we recorded the time taken to complete the puzzle; and if the child did not solve the puzzle, we recorded 5 min as completion time. A move was defined as a child lifting a disk from a peg and placing it back on the same peg, or on to another. When the child violated any of the three rules (outlined in the Materials section), the experimenter informed the child of the rule break. In that case, we counted both the rule breaking move and the subsequent correcting move as separate complete moves.

We examined two dependent variables, "Total Moves" and "Time per Move." Time per Move was computed by dividing the time by the number of moves. Total Moves was the number of moves the child made to complete the puzzle (or within the 5 min if they did not complete the task).

To assess coder reliability a second observer coded for Total Moves with randomly selected subset of participants ($n = 33$ trials). Krippendorff's alpha for interval data was computed at 0.988 verifying a high level of agreement across observers. Fewer than 15% of the individual scores for any trial differed across

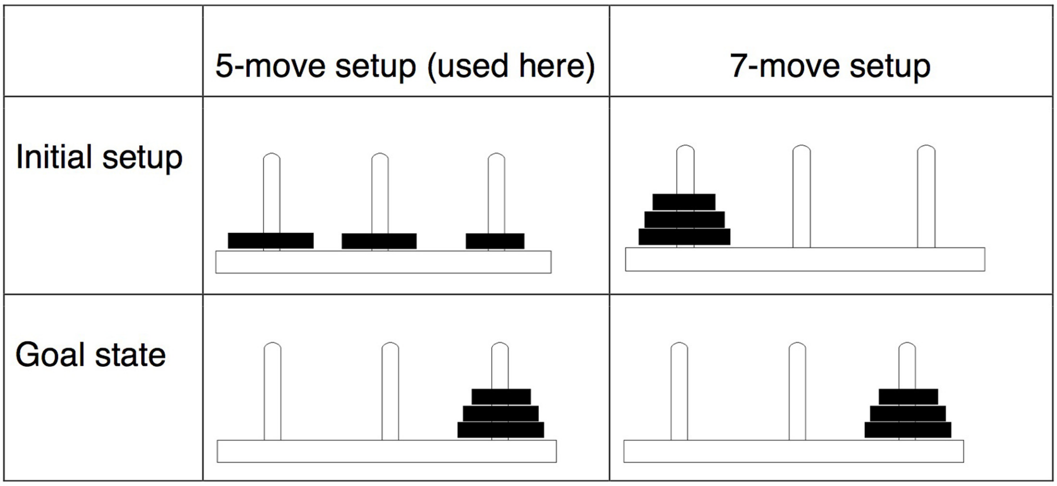

FIGURE 1 | Initial state and goal state of the 5-move and 7-move Tower of Hanoi puzzle.

the observers and when there were differences, there were no differences in the ranked order of the scores across the four trials.

RESULTS

Total Moves Analysis

Figure 2 shows the Total Moves data. Data was analyzed using a full factorial repeated measures regression on Total Moves with condition and age (as a continuous variable) as between subjects predictors and trial number (1 vs. 4) as a within subject predictor. There were no significant main effects of condition, age, or trial. However, the analysis did reveal a significant age by trial number interaction, $F(1,43) = 6.75$, $p = 0.01$, $\eta^2 = 0.14$. Further analyses demonstrated that the interaction was driven by the fact that older children improved from trial 1 to trial 4, but younger children did not improve. We confirmed this by examining the older and younger children separately with a matched pairs t-test, dividing the groups with a median split on age, resulting in relatively equal sized groups ($n = 25$, $n = 24$). Older children (M age: 5.6 years; SD: 0.66; Range: 4.58–6.5; 44% male), improved significantly from trial 1 to 4, $t(24) = -4.01$, $p < 0.001$, Cohen's $d = 0.80$, whereas younger children (M age: 3.79 years; SD: 0.46; Range: 3.08–4.42; 46% male) did not improve, $t(23) = 0.96$, $p = 0.35$.

Huber et al. (2016) found that Total Moves decreased from the 1st to 4th trial, regardless of whether the practice trials were in 2D or and 3D modality. The results from the older group in the current study replicates this finding. However, in the current analysis the age range for the older group (4.58 to 6.50 years) differed somewhat from the reference study (4.05 to 6.50 years). For a more precise comparison to the reference study, we applied an ANOVA on Total Moves for all children older than 4 years of age. This ANOVA used condition as a between subjects predictor and trial as a repeated-measure. Consistent with Huber et al. (2016) there was a significant effect of trial, $F(1,33) = 16.70$, $p < 0.001$, Cohen's $d = 0.68$, but no effect of condition ($F = 1.35$), nor a trial by condition interaction ($F = 0.62$).

Time per Move Analysis

Data was analyzed using a full-factorial repeated measures regression on Time per Move with condition and age as between subjects predictors and trial number (1 vs. 4) as a within subject predictor. The results of this analysis revealed a main effect of age, $F(1,43) = 17.8$, $p < 0.001$, with moves being made, on average, 0.99 s faster with each year of age. Additionally, it revealed a trial by condition interaction, $F(1,43) = 3.43$, $p = 0.04$. This interaction reflects that children in the 3D-3D-3D-3D condition improved their move speed by 4.36 s from trial 1 to trial 4, whereas the 3D-2D-2D-3D and 2D-2D-2D-3D conditions improved only by 0.93 and 0.83 s, respectively. Given that the 3D-3D-3D-3D group had the most practice moving disks in a single modality, this effect is not surprising. It is also consistent with the original finding that children in the 2D-2D-2D-3D condition did not become significantly faster from baseline to test. There were no other significant main effects or interactions resulting from this analysis.

Because the reference study did report a significant effect of trial, with children making moves more quickly by trial 4, an additional analysis was conducted with children aged over 4 years (consistent with the reference study). An ANOVA with condition as a between subjects factor and trial as a repeated measure revealed a significant effect of trial for this group of 4- through 6-year-olds, $F(1,46) = 10.29$, $p = 0.002$, Cohen's $d = 0.74$.

DISCUSSION

The main contribution of this work is the verification that children over 4 years of age can learn to solve a problem using a touchscreen app and transfer this learning to solve an isometric

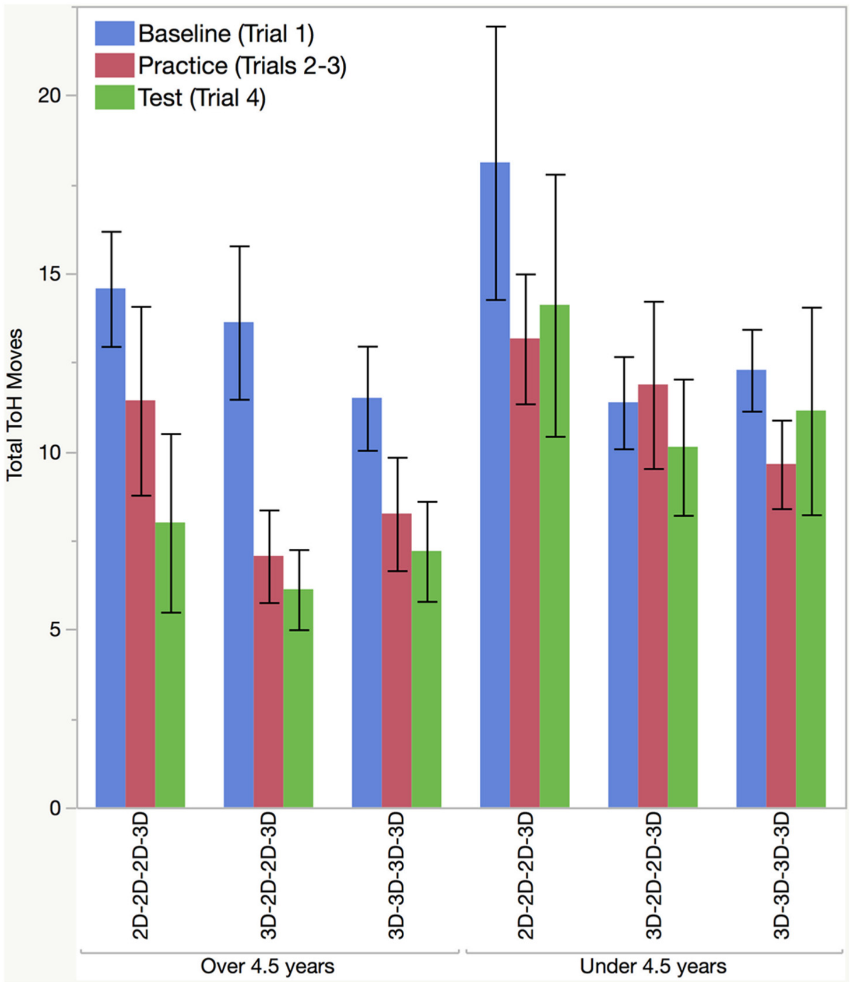

FIGURE 2 | Number of moves taken to solve task by condition, trial, and age group. Analyses were performed on Trials 1 and 4. Practice trials bars are the mean of Trials 2 and 3. Error bars reflect standard errors.

problem in the physical world. This finding, originally reported by Huber et al. (2016) with Australian children, is replicated here with a sample of preschool children in Croatia.

Huber et al. (2016) studied children ages 4 to 6 years of age. Total Moves and Time per Move significantly decreased from the initial baseline trial to the final test trial. This was the case, regardless of whether the children practiced the task in the 2D or 3D modality. The current study confirms these findings.

The similarity in results across the two studies underscore the validity of a number of points made in the reference study. In particular, the findings that children smoothly transferred the problem-solving skill that they practiced in 2D to apply to the 3D model illustrates the limits of 'screen time' as a construct. 'Screen time' does not distinguish activities that involve active engagement from those that involve only passive viewing. While children may have problems learning problem-solving strategies from certain screen-based activities, the current and reference studies demonstrate that not all screen time has the same learning value.

Indeed, the current task appears to require cognitive engagement adequately complex to result in problem-solving learning (e.g., Bauer and Mandler, 1992). Consistent with these findings are those of Wang et al. (2017), which report that 5- to 6-year-old children, learned how to tell time from a touchscreen time-telling app and then apply what they had learned from the touchscreen to a toy clock. Both our tasks and theirs required children to focus on rules and thus contrast imitation tasks where greater attention may be given to the superficial differences around modality.

In the current study, the children under 4 years of age showed little ability to improve at the ToH problem regardless of the practice modality. That finding may result from using a task that is not suitable for children of that age. For further research with the younger age group, a suitable option may be to use a different but common implementation of the ToH task, i.e., begin with the 2-disk version, then the 3-disk version, and increase the number of disks by one until the child cannot complete task. The performance variable would be scored as the greatest number of disks with which each child successfully completed the puzzle.

While the current experiment verifies the finding of the reference study, it is notable that in both studies children received instructions about how to complete the task from a live experimenter. They were not simply given a touch screen device and left to learn the task alone. Zack and Barr (2016) demonstrated the impact of adult scaffolding when young children use a touch screen device, with 15-month-old infants more likely to transfer learning between a touch screen device and a physical object when they had high levels of scaffolding. Future research could build on the current study and manipulate how the initial instructions are given—via a touchscreen app or from live experimenter. This could address whether the social interaction involved in the procedure impacts the children's learning.

Finally, the replication of results despite the study originally being undertaken in Australia, and this time in Croatia strengthens the validity of the findings. Furthermore, transferring the problem-solving skills to complete the ToH task has now been demonstrated by both English speaking and Croatian speaking children.

CONCLUSION

This study replicates the findings of the Huber et al. (2016) study and showed that children 4 years and older can transfer learning from 2D to 3D, even without exposure to 3D prior to the 2D exposure. We found that children under 4 years do not appear to improve their ability to solve the ToH problem with either the touch screen or the physical model.

AUTHOR CONTRIBUTIONS

Conceived and designed the experiment: JT and JK. Performed the experiment: AD. Analyzed the data: JT and JK. Wrote the paper: JT, JK, and AD.

FUNDING

This research was supported by financial donations from the Croatian companies Damaco d.o.o and Bina-Istra from whom there was no involvement in the study design; in the collection, analysis, and interpretation of data; nor in the writing of the report; nor in the decision to submit the article for publication.

ACKNOWLEDGMENTS

The authors would like to thank the families of the children that participated in the experiment. We also thank Allan Kaufman for his editing services.

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Conflict of Interest Statement: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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ORIGINAL RESEARCH
published: 16 May 2017
doi: 10.3389/fpsyg.2017.00677

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Parent–Toddler Behavior and Language Differ When Reading Electronic and Print Picture Books

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Little is known about the language and behaviors that typically occur when adults read electronic books with infants and toddlers, and which are supportive of learning. In this study, we report differences in parent and child behavior and language when reading print versus electronic versions of the same books, and investigate links between behavior and vocabulary learning. Parents of 102 toddlers aged 17–26 months were randomly assigned to read two commercially available electronic books or two print format books with identical content with their toddler. After reading, children were asked to identify an animal labeled in one of the books in both two-dimensional (pictures) and three-dimensional (replica objects) formats. Toddlers who were read the electronic books paid more attention, made themselves more available for reading, displayed more positive affect, participated in more page turns, and produced more content-related comments during reading than those who were read the print versions of the books. Toddlers also correctly identified a novel animal labeled in the book more often when they had read the electronic than the traditional print books. Availability for reading and attention to the book acted as mediators in predicting children's animal choice at test, suggesting that electronic books supported children's learning by way of increasing their engagement and attention. In contrast to prior studies conducted with older children, there was no difference between conditions in behavioral or off-topic talk for either parents or children. More research is needed to determine the potential hazards and benefits of new media formats for very young children.

Keywords: shared reading, e-books, toddlers, parent–child interaction, media

OPEN ACCESS

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Specialty section:
This article was submitted to Developmental Psychology, a section of the journal Frontiers in Psychology

Received: *01 October 2016*
Accepted: *13 April 2017*
Published: *16 May 2017*

Citation:
Strouse GA and Ganea PA (2017) Parent–Toddler Behavior and Language Differ When Reading Electronic and Print Picture Books. Front. Psychol. 8:677. doi: 10.3389/fpsyg.2017.00677

INTRODUCTION

Researchers have long acknowledged the importance of children's environment in their language development (Hart and Risley, 1995; Snow, 1983). Shared book reading is one activity that can be particularly supportive of language development. Shared reading with preschoolers is linked with language growth and emergent literacy skills (National Early Literacy Panel, 2008; Sénéchal et al., 2008); and infant–caregiver reading is predictive of vocabulary growth (Debaryshe, 1993; High et al., 2000; Karrass and Braungart-Rieker, 2005).

Electronic books also carry some literacy benefits (Zucker et al., 2009; Takacs et al., 2015). Research on early versions of electronic books, such as CD-ROM books played on computers, shows that preschool and elementary children learn important literacy skills from electronic books, including phonological skills (Chera and Wood, 2003; Littleton et al., 2006; Shamir and Korat, 2007), vocabulary (Segers and Verhoeven, 2002; Shamir and Korat, 2007; Ihmeideh, 2014), print awareness (Ihmeideh, 2014), word reading (Shamir and Korat, 2007; Segal-Drori et al., 2010) and story comprehension (Doty et al., 2001). Because of the extra features they incorporate, such as built-in dictionaries and animations of story events, electronic books may support the development of literacy skills to an even greater extent than books without these enhancements (Rehbein et al., 2002; Verhallen et al., 2006; Korat and Shamir, 2008, 2012). A recent meta-analysis concluded that electronic books support story comprehension and vocabulary gains beyond that provided by print books (Takacs et al., 2015). However, electronic book studies have focused on pre-readers, early readers, and readers (ages 3 and up). Literacy benefits to infants and toddlers may differ.

One important mechanism by which shared reading with pre-readers impacts language development is through the adult–child interactions that take place during reading (Mol et al., 2008). If electronic books serve to disrupt the interactions that adults and young children have during reading, that may play a detrimental role in the literacy development of very young children. There is reason to believe that important differences exist in the way parents and children interact with new technologies and traditional formats (Chiong et al., 2012; Parish-Morris et al., 2013; Krcmar and Cingel, 2014; Willoughby et al., 2015). In the current study, we extend the literature on parent–child picture-book reading by investigating the impact of the book's medium on the language and non-verbal behaviors parents and their 17- to 26-month-old children use during reading. We also take steps to address whether differences in parent and child behavior and talk during reading may be linked to differences in learning new information from the picture book. We first review prior research on traditional picture-book reading with this age group to reveal adult and child behaviors during reading which may impact learning and then present the emerging literature on shared reading in digital formats. Taken together this research informs our hypotheses regarding potential medium-related differences in parent–child reading behaviors.

Shared Reading with Print Picture Books

To identify parent and child behaviors important to learning in reading contexts with our target age group, we reviewed the literature on shared reading with children under the age of 3. Two main categories emerged: non-verbal behaviors and parent–child talk. Parent and child behaviors in these categories vary in response to the age and linguistic growth of children. According to this research, parents of children under 18 months use both verbal and non-verbal attention-grabbing techniques and provide many labels during reading (DeLoache and DeMendoza, 1987; Sénéchal et al., 1995; Martin, 1997). They often point and ask simple questions, and interactions may be comprised of simple linear turn-taking (Sénéchal et al., 1995). This contrasts with parents of older toddlers and preschoolers who rely less on non-verbal behaviors and labeling to direct attention and use more complex speech in more extended reciprocal interactions (DeLoache and DeMendoza, 1987; Goodsitt et al., 1988; Sénéchal et al., 1995; Martin, 1997).

Non-verbal Behaviors and Affect

Unfortunately we found no literature directly linking non-verbal behaviors with literacy growth. However, because non-verbal behaviors play an important role in attention directing, they may be influential in children's language learning. DeLoache and DeMendoza (1987) reported that infants often used pointing during reading to initiate interactions with their parents, especially at 15 months. Mothers interpreted their infants' points as requests for information and generally provided a label. Murphy (1978) observed that pointing during reading was often accompanied by a verbal label from the mother when children were 14 months, but that by 20 months mothers instead asked children to provide the label for the referent. Thus, pointing may initiate and direct interactions in which language learning occurs.

Additionally, young children's engagement in the reading process may be enhanced by giving them control to turn the pages of the book. Observations of parents and infants indicate that infant page turning increases as infants approach 12–14 months, is quite popular through the second year of life, and decreases in frequency around 24 months (Murphy, 1978; Martin, 1997; Loeb et al., 2015). Goodsitt et al. (1988) also reported a decrease in child page turns between 2 and 3.5 years of age. Murphy (1978) argues that once children have mastered the page-turning activity they shift their focus to looking at the pictures in the book. Goodsitt et al. (1988) add that mothers may encourage young children to practice page turns as part of learning the "rules" of reading. In addition, younger children may be more reliant on physical actions to maintain engagement in reading. Thus, we include both pointing and page turns as potentially important behaviors that may enhance toddlers' shared reading experiences.

The emotional quality of the reading interaction may also play a potential role in supporting learning from shared reading. Research with preschool and elementary children indicates that the affective quality of reading interactions predicts children's motivation for reading (Sonnenschein and Munsterman, 2002), frequency of reading (Leseman and de Jong, 1998; de Jong and Leseman, 2001), quality of parent language during reading (Leseman and de Jong, 1998; de Jong and Leseman, 2001), and children's emergent reading skills (Bingham, 2007). Research on the emotional quality of the reading interaction with younger children is limited and suggests a complex interaction with cultural variables and reading styles (Cline and Edwards, 2013, 2017). However, because of its importance in older groups we decided to include a measure of child affect in our study.

Parent and Child Talk

Parent language, especially talk that is adaptive based on the developmental level of the child and results in increased child talk, is an important component of reading interventions that are successful in increasing preschoolers' language acquisition (e.g., Whitehurst et al., 1988). Many have argued that the progression of parent language from simple to more complex is supportive for younger children's language development as well (e.g., DeLoache and DeMendoza, 1987; Goodsitt et al., 1988). However, specific information about the best language to use when reading with children ages 2 and under is an area open for further study.

Two studies have indicated that particular types of parent language are associated with more talk on the part of their young co-readers. Sénéchal et al. (1995) noted that 9-, 17-, and 27-month-olds talked more when parents asked more questions and provided more feedback. Fletcher and Finch (2015) also found that 2-year-olds were more responsive when they were asked questions and received positive feedback, at least when reading non-narrative text. In addition, toddlers responded more when parents used more verbal attention-getting statements. Thus, questions, feedback, and attention-getters may be beneficial, but more research is needed to establish causal directionality and links with child language growth.

Links with Learning

The non-verbal and verbal behaviors reviewed above have not been directly linked to toddlers' language learning, but have been shown or predicted to increase engagement with reading by way of increased verbal and non-verbal participation and attention to the book. Overall child attention and engagement during reading *has* been linked to developmental benefits. Children's verbal and non-verbal responses during reading at age 2 predicted their language ability at 2.5 and 4 years (Crain-Thoreson and Dale, 1992), and 14-month-olds' verbal and non-verbal responses, rated interest, and time spent reading predicted language development at 18 months (Laakso et al., 1999). Fletcher et al. (2005) observed children repeatedly between age 18 and 24 months and found high stability in individual children's responsiveness (verbal and non-verbal participation) to reading and joint attention to the book across sessions. There was also a correlation between children's attention and their vocabulary at 24 months. Thus, it is possible that attention and engagement partially mediate the path between the non-verbal and verbal behaviors identified above and toddlers' language acquisition during reading.

In the current study, we add to the literature on traditional parent–child picture-book reading by reporting measures of parent and child non-verbal and verbal behaviors similar to those reviewed above. We extend the literature by also incorporating a vocabulary learning outcome. A growing number of studies have shown that by 18 months children learn specific words presented to them during a picture-book reading interaction (Ganea et al., 2008; Tare et al., 2010; Horst et al., 2011; Walker et al., 2013). We included a test of learning of a specific word presented in the book to assess whether language learning occurred during the particular parent–child reading session and with the goal of answering whether any measured parent and child behaviors were mediators of this learning.

In summary, research on shared reading of print books has lead us to identify both non-verbal behaviors (pointing, page turns, child affect) and aspects of parent and child language (amount and content of parent and child talk) that may serve to increase toddlers' learning during picture book interactions. In the current study we observe these variables during a parent–child reading session with either print- or electronic-format books. Our goal is to document format-related differences in these behaviors, as well as potential links between the identified behaviors and children's learning. In the next section we review the emerging literature on shared reading with electronic books to inform our hypotheses regarding potential format-related differences in behavior and learning.

Shared Reading with Electronic Books

Electronic books include a number of enhancements that may lead to different parent and child behaviors and child learning than print books. For example, many electronic books read themselves and include animated pictures and games. Research with preschoolers and kindergarteners has addressed the pros and cons of including digital scaffolding, picture cues, read-alouds, highlighted text, word pronunciations, built in dictionaries, and other features (see Moody, 2010; Takacs et al., 2015). Takacs et al.'s (2015) meta-analysis revealed that multimedia features like animations and sound effects were supportive of vocabulary and story comprehension, whereas built-in games and hotspots (spots on the screen that lead to an on-screen event when activated) detracted from learning. Studies have not yet addressed how most of these individual features influence adult–child interaction, but one meta-analysis suggests that multimedia features, taken together, may be equally effective for children's learning as scaffolding by an adult (Takacs et al., 2014). The authors argue that "multimedia elements provide scaffolding of children's understanding and word learning that is comparable to adult scaffolding during storybook reading (p. 10)." Thus, it is possible that multimedia books afford less parent–child talk because the child is focused on and learning from the narration and animation in the book, rather than scaffolds from a parent.

A few studies have investigated the role of the electronic format on adult and preschooler behaviors while reading. Moody et al. (2010) found that 3- to 6-year-olds in Head Start classrooms labeled more pictures when they were read a print book than when they read the same book in electronic format. Children also tended to label more pictures when their hotspot usage in the electronic book was restricted than when they were free to activate as many hotspots as they desired. Other types of child talk did not differ based on medium, but labeling was one of the most frequent ways in which children initiated communication with their co-reader, a trained research assistant. In this study children were most communicative when reading print books and least communicative when reading electronic books with many distracting hotspots, possibly indicating that hotspots drew their attention away from their in-person interaction. In a more recent study, 3- to 5-year-olds who read electronic and print storybooks made a similar number of overall utterances with both book types, but made more story-related references with print books and more comments about the book/device itself with the electronic books (Richter and Courage, 2017).

Three recent studies with preschoolers reading with their parents have resulted in similar findings regarding parent language. In three different studies, parents were observed reading electronic or print books with their children and children were tested on their story comprehension. In all three studies, there was evidence that parents reading electronic books spent less time talking about story-related content and more time on off-topic (usually device-related) talk than parents reading print stories (Chiong et al., 2012 – 3- to 6-year-olds; Krcmar and Cingel, 2014 – 2- to 5-year-olds; Parish-Morris et al., 2013 – 3- and 5-year-olds). There was also evidence that children's story comprehension was lower when reading electronic books with all groups except Parish-Morris and colleague's older group, who reached ceiling on the comprehension measure. The authors argued that one reason for the lower comprehension scores may have been the lower quality of parent language during reading. This was the case both with electronic console books (Parish-Morris et al., 2013) and iPad books (Chiong et al., 2012; Krcmar and Cingel, 2014).

One important difference between these three similar studies did arise: Chiong et al. (2012) reported that the reduction in content-related talk (compared to print books) was only present when parents read an enhanced e-book with hotspots with their children, and not when reading a basic electronic version in which no hotspots were present. Similarly, there was no reduction in comprehension for the basic electronic book, although there was an increase in non-content-related talk (again, compared to the print book). This suggests that the addition of interactive features to the book was what distracted parents and children from the story, not the device itself. On the other hand, Krcmar and Cingel (2014), using a basic book without hotspots, reported a decrease in content-related talk, increase in non-content-related talk, and decrease in comprehension with electronic compared to print books. Interestingly, Krcmar and Cingel also reported a negative relationship between prior electronic book experience and children's comprehension of the electronic book. They suggested that children with more experience with iPads may view them as toys and invest less mental effort in learning from them. If true, an increase in the prevalence of home iPad use between 2012 and 2014 could partially explain the discrepancy in the two studies' findings.

None of these studies have reported parent and child talk with electronic books in children under the age of 2. However, in one study parents of 1- to 4-year-olds self-reported that they less frequently labeled items in stories or stopped to discuss stories when reading electronic books with their children than when reading print, and that their children were less likely to label items in electronic stories or tell back parts of the story (Strouse and Ganea, 2017a). These reports appear to be consistent with the findings regarding parent–child talk observed in older samples.

Parents in Strouse and Ganea's (2017a) study also reported that they and their children were less likely to point when reading electronic than print books. Differences in pointing and other non-verbal behaviors may be afforded by the different media platforms as well. For example, one study of 3- and 4-year-olds in classrooms indicated that children who were able to hold an electronic device during reading were more likely to look at and touch the device whereas those who did not hold the device were more likely to gesture (Roskos et al., 2012). If infants are likely to be holding the device on which they are reading they may be less likely to point and more likely to touch the device. In another study with 4-year-olds, children were more likely to physically control an electronic than a print book when reading with their parents (Lauricella et al., 2014). Thus, differences in how the parent–child pair hold electronic versus print books may result in format-related differences in gesturing. In addition, the physical action need to turn an electronic page requires a touch rather than a physical flip. Because tapping is a simpler motor movement it may be more easily available to infants and toddlers than print-book page turns.

Despite reports that content-related talk and physical gesturing are infrequent there is evidence that an electronic format is more engaging for children. Richter and Courage (2017) reported that 3- to 5-year-olds stated a preference for the electronic books over the print books in their study. Chiong et al. (2012) reported that their 3- to 6-year-olds were more engaged with both types of electronic books they used (enhanced and basic) than print books. Moody et al. (2010) reported that a group of Head Start preschoolers who read an electronic book with an adult maintained participation in reading longer than a group who read a print book. Finally, Verhallen and Bus (2009) found that 5-year-olds with low language skills invested more mental effort across multiple readings when books were animated rather than comprised of static images, suggesting that enhancements available in electronic formats acted to maintain interest in reading. We know of no studies measuring the interest level of children younger than 3, but expect that children in this age group will find touchscreens a particularly engaging medium because they are so effortless for young children to control.

Based on research with print books, we expect that parent–child talk in our age range (17–26 months) will consist of exchanges of fairly low complexity that are focused on simple labeling and pointing rather than multifaceted connections. Device-related talk may not impair learning from these kinds of low-complexity interactions because they do not depend on drawing connections across multiple story aspects. However, any differences in the amount of pointing and labeling between the two formats (as parents reported in Strouse and Ganea's, 2017a) survey may influence word learning because children in this age range often rely on adult referential cues like pointing to identify the referent of new words (Baldwin, 1993; Grassmann and Tomasello, 2010). It is also possible that animations in the electronic book would support children's word learning in the absence of referential cues from an adult, as 18-month-olds have also been shown to use salience cues like illumination and movement when learning words (Moore et al., 1999). It remains to be seen whether animations could provide similarly supportive referential cues as adults for children in this age range.

Beyond differences in word learning resulting from the presence or absence of attention-directing cues, there is reason to suspect medium-related differences in learning even when these cues are matched. In Strouse and Ganea's (2017b) study, 17- to 23-month-old children were read either an electronic or print book with no text, animations, or sounds in a short, scripted interaction with a researcher. Pointing and labeling were scripted and equivalent across conditions, and animations were absent. Children were then tested on a new word presented in the book. Toddlers displayed more transfer and generalization of the newly learned word when they were read a print rather than electronic version. The authors hypothesized that this difference may have been a result of expectations children brought to the learning situation built on prior experience with the formats (Strouse and Ganea, 2017b). Thus, there is reason to expect that even well-matched books may result in differences in learning.

Research Hypotheses

Analyses will be conducted to address the following hypotheses:

H1: Parents will produce less pointing and content-related language and more off-topic and behavior-related language with electronic than print books.

H2a: Children will produce less pointing and child-initiated content-related language with electronic than print books. Children with prior experience with e-reading may produce less content-related talk when reading in the electronic format than those without experience.

H2b: Children will exhibit higher levels of attention and engagement with electronic than print books. Because of increased engagement, we also expect children will display higher levels of positive affect with electronic than print books.

H3: Children read electronic books will display less learning than those read print books. Prior experience with electronic books will be associated with lower learning from electronic books, but play no role in learning from print books.

Finally, in this study we are interested in the role that parent and child behaviors during reading play in mediating the relationship between book format and learning. Potential mediators will be identified from behaviors with large format-based effects.

MATERIALS AND METHODS

Participants

Participants were 152 children aged 17.0–26.9 months ($M = 21.33$, $SD = 2.90$; 77 male) from Toronto, Ontario and surrounding areas. They were recruited through advertisements, local street fairs, child care centers, and the local Science Centre. One hundred and two of these children were randomly assigned to the two experimental conditions: 50 were read electronic books and 52 were read print books. The remaining 50 children were randomly assigned to two control groups: 25 in electronic format and 25 in print format. Children in the control conditions did not read books but were tested on the learning outcome. Ten additional children were not included in the analyses due to unwillingness to participate in the procedure (8), having the book at home (1), and technical difficulties with the recording (1). Children who participated had no developmental delays and were exposed to English at least 50% of the time.

This study was carried out in accordance with the approval of the University of Toronto Research Ethics Board and written informed consent was obtained from all parents. The final sample was identified by their parents as 67.8% White and 19.7% mixed ethnicity. The remaining participants were identified as Asian (9 children, 5.9%), African–Canadian (2 children, 1.3%), and "other" ethnicity (3 children, 2.0%). Five parents (3.3%) opted not to respond. Parents were generally well-educated, with a median and modal response of a 4-year university degree.

Materials

Picture Book

Children in the experimental conditions were randomly assigned to be read either electronic or print versions of two 10-page picture books by their parents. The electronic books were commercially available by a major worldwide book publisher. The app containing the books was listed as "educational," including claims such as, "Helps to develop hand-eye coordination and focusing skills in young babies," and, "Helps older babies and toddlers with language acquisition." Each book introduced four animals in two-page sequences. The first page featured an adult animal of a species and the second page introduced the baby animal by name (e.g., joey for a baby koala). We chose two books, one which presented farm animals (sheep, duck, horse, cow) with which parents reported most children were already familiar, and one which presented wild animals (lion, zebra, koala, crocodile) with which parents reported most children were less familiar. Both books also included two final pages including a vehicle and a human baby.

The electronic book included background music, animation, and sound effects for each page as well as an automatic voiceover that read the text. The text was comprised of 1–2 sentences per page with 3–4 words per sentence (e.g., Hello, fuzzy ducklings!). The animations and sounds played automatically as each page was turned, and there were no actions or hotspots for parents and children to tap for extra features. A tap was required to turn each page, and this was the only action that produced a contingent response.

The publisher of the electronic book has a similar line of printed board books with very comparable content and illustrations, however, we could not find an exact printed match for the electronic book. As a result, our print book was created by taking screenshots of each page of the electronic book. These were printed, laminated, and bound. Books were printed to be the exact size they appeared on the tablet screen. Children in the two control groups were not read any of the books.

Test Items

All children (experimental and control) were tested on their receptive understanding of two animal names. At the beginning of the session, parents were given a checklist of 16 animal names – 8 that were presented in the two books used in this study along with 8 animals from other books from the same published set. Parents were asked to identify which animal names their child understood, understood and said, or did not know. Based on these parent reports we selected animals individually for each child to use for testing.

To test for word learning from the book, we chose an *unfamiliar target* randomly from among the child's unknown animals from the wild animal book (lion, koala, zebra, crocodile). We then chose two distractor animals: another from the wild book (*seen distractor*) and an *unseen distractor* from a book the child did not read, either a seahorse or a whale. Children who did not have enough unfamiliar animals to create this set of three animals to be tested with were excluded from the analyses related to learning. Sixty-three children – 42 experimental (20 who read e-books, 22 who read print books) and 21 control – were retained for these analyses.

Each child was also tested with a familiar set of animals as an indicator of the child's understanding of and compliance with the testing procedure. For each child's familiar animal testing, we randomly chose a *familiar target* from among each child's known animals from the farm book (sheep, duck, horse, cow). We then chose two distractor animals from the child's remaining known animals, one *seen distractor* from the farm book and an *unseen distractor* animal, either a frog or a bird. For all choices, names the child said were prioritized above those the child understood but did not say.

Children were asked to identify each target animal (familiar and unfamiliar) three times: using a cartoon drawing of each target animal taken from screenshots of the book, with a photograph of each real target animal, and with small plastic replicas of the animals. For the two-dimensional trials (cartoon and photograph), children in the print book conditions were tested with laminated cards of the animals and children in the electronic book conditions were tested with the same pictures on the tablet screen. The images appeared the same size on the cards and on screen. Children in all conditions were tested with the same replica animals.

Questionnaires

Parents were asked to fill out the MacArthur-Bates Communicative Development Inventory Short Form Level II (Fenson et al., 2000). This measure is comprised of a checklist of 100 words for which parents indicated whether their child said each word. Children had vocabularies around average for their age. Parents checked an average of $M = 41.0$ words ($SD = 25.9$) on the MacArthur-Bates checklist (percentile: $M = 44.1$, $SD = 29.0$).

Parents were also asked to fill out a questionnaire which included demographic information for the family and information about their child's exposure to English, their child's knowledge of the animal names in the books, and their experiences with shared picture book reading, electronic books, videos, and other media.

Parents of 21% of children reported that they had prior experience with e-books. Of the parents who reported each activity, parents estimated that their children were read traditional print books an average of 5.6 h per week ($SD = 4.36$), read e-books 1.29 h per week ($SD = 1.88$), watched 3.43 h of videos and television ($SD = 4.32$), and played 1.01 h of apps and games ($SD = 1.82$).

Procedure

The experimenter began by warming up with the child by playing on the floor with puzzles or other toys (on campus) or at a child-sized table with stickers and coloring materials (at the Science Centre) while the parent completed the questionnaire and vocabulary checklists. Once the child was comfortable, the child and parent were invited to the testing area.

Reading

Children and parents were encouraged to sit however they felt most comfortable for reading. This included sitting in an armchair with the child on their lap, sitting at a child-sized table next to the child, sitting together on the floor, and other positions.

Parent–child pairs were randomly assigned to participate in one of two experimental conditions (print or electronic book) or in one of two (print or electronic) control conditions[1]. Half of parents in each experimental condition were asked to read the farm book first; half read the wild book first. After setting up a camera and audio recorder, the experimenter left the room to allow parents and children to read without distraction. She returned to the room when she heard that the pair had finished reading. Parent–child pairs participating in the control conditions did not read the book and participated only in the following test.

Test

Parents and children were not aware that children would be tested on the animal names until after they finished completing the animal checklist and, in the experimental groups, completed reading the books. The experimenter began by exclaiming, "Now I need your help to find some animals!" For each of the test trials she presented the children with the three animal pictures or replicas, allowed the child to touch them if they wanted, and then asked the child to "Show me the [target]!" Once the child made a choice, the experimenter replied, "Thank you!" and continued to the next trial. There were six total trials (three with familiar animals and three with unfamiliar animals). The order of the two sets of animals (familiar and unfamiliar) and two picture formats (cartoon images taken from the book and photographs of real animals) were counterbalanced. The two sets of replica animals were always presented last. Within each set, the unseen distractor was always placed in the center. The target and seen distractor alternated in the left and right positions.

Transcription

Parents and children's reading sessions were transcribed from video using CLAN[2]. In four cases the original videos were lost and sessions were transcribed from audio recordings. Transcription began when parents opened the print book or tapped the icon to begin the electronic book. Transcription ended when the book was closed.

[1] Half of the parents in each experimental condition were asked to read "as they would if they had this book at home" and half were asked to "use this book to teach your child any of the animal names he/she does not already know." This manipulation was initially included in our analyses, however, no patterns important to the hypotheses or the statistical models reported in this paper emerged, so we collapsed these groups and this instruction is not discussed further.

[2] http://talkbank.org/clan/

Coding

All coders were blind to study hypotheses.

Non-verbal tactile behaviors

Parents' and children's book-related tactile behaviors were coded offline using the Datavyu program[3]. Two coders reviewed the videos and recorded the number of times children and parents pointed at the book or turned the pages of the book. Reliability for 21% of the sample, measured by the intraclass correlation coefficient, was $r = 0.90$ for child points, $r = 0.91$ for child page turns, $r = 0.93$ for parent points and $r = 0.95$ for parent page turns.

Child language

Coders reviewed transcripts of the parent–child reading sessions and assigned each child utterance to one of the following categories: book content-related talk (e.g., "moo"), book behavior-related talk (e.g., "turn page," "touch"), and off-task comments. Book content-related talk was further broken into three categories: child-initiated comments, questions, and responses. The number of utterances in each category was summed for each child for each book. A second person coded approximately 50% of the videos. Interrater reliabilities, measured by the intraclass correlation coefficient, were: book-related comments, $r = 0.83$, book-related questions, $r = 1.0$; book-related responses, $r = 0.89$; book-related behavioral talk, $r = 0.63$; and off-task talk, $r = 0.83$. Questions were extremely rare and were thus excluded from analyses.

Parent language

Parent utterances were also assigned to categories from the session transcripts. Coders initially assigned parent speech to book-content-related speech, orienting talk (i.e., comments designed to redirect children's attention to the book or to do book-related behaviors), direct reading of book text, or off-task talk. Book-content-related speech was further broken into questions, simple statements about things directly observable in the book, elaborations about book content that went beyond the information provided, negative or positive feedback given to the child, and simple repetition of child speech. The number of utterances in each category was summed for each parent for each book. Utterances were coded by a second individual for approximately 50% of the sample. Intraclass correlations were: questions, $r = 0.96$; simple statements about content, $r = 0.91$; elaborations, $r = 0.62$; feedback, $r = 0.67$; repetitions, $r = 0.65$; orienting/behavior-related speech, $r = 0.81$; reading, $r = 0.96$; and off-task speech, $r = 0.90$.

Patterns of parent content-related talk (i.e., questions, statements, elaborations, feedback, and repetitions) were consistent with what we expected in this age group (high numbers of simple statements and questions) and consistent across categories, so parent content-related talk was combined into a total score for analysis. Direct reading of text from the page of the book was coded into a separate category that was not included in our analysis of parent content-related talk. This was done, in part, to control for differences that resulted from the automatic narration in the electronic book.

Attention

Children's attention to the book during reading was coded offline as a proportion of time their eyes were on the book while the book was open/on screen. Children who went off camera for less than 30 s during a book-read were given a proportion out of the total codeable time; those off-screen for more than 30 s were not coded. A second person coded 31% of the participants in the groups who read. Coders had an intraclass correlation of $r = 0.89$.

Global behaviors (engagement and affect)

Children's availability for reading, their affect, and active participation were coded from video by two coders using Likert scales adapted from Deckner et al. (2006). The book reading sessions were partitioned into 30-s intervals and a code was assigned to each interval with at least 15 s of codeable time (child viewable on screen and book open for reading). Availability for reading was measured from 1 = child had less than 3 s during the interval in which they were present and attending to the book to 5 = the child was present and not looking away for at least 27 s during the interval. Affect was measured from 1 = child protesting or crying for at least 7 s during the interval to 5 = child laughing or smiling for at least 7 s during the interval. Active participation was measured from 1 = child made no contributions during the interval to 5 = child made 7 or more verbal or physical contributions including comments, gestures, and manipulations such as turning the pages or pointing. Interrater agreement for 20% of the sample, measured using a weighted Kappa, was $\kappa = 0.89$ for availability, $\kappa = 0.70$ for affect, and $\kappa = 0.81$ for active participation. Scores for the 30-s intervals were then averaged for a composite score for each scale for each book the child was read.

Animal choice (learning)

Children's animal choices during the test trials were recorded by the experimenter as the child's first touch after the question prompt. A second coder reviewed children's choices from video. Reliability was $\kappa = 0.78$. A third coder resolved all discrepancies.

Missing Data

Two children in the reading groups were unwilling to read the farm book and were thus missing data for all variables for that book. Their data for the wild book was retained. Because children were sometimes out of range of the camera or their sessions were transcribed from audio, four children were missing data for non-verbal behaviors for both books, three additional were missing a total duration score for one of the books, and another eight were missing one or both attention scores. Because missing data resulted from poor camera angles or lost videos, there is no reason to suspect missing data was systematic. Because children were often only missing a score for one of the two reads, we purposefully chose an analysis strategy that would allow us to retain their other scores without needing to impute or replace the missing values.

[3]http://datavyu.org

RESULTS

Preliminary Analyses

The number of children in each condition with prior exposure to e-books did not significantly differ, but this variable was used as a covariate in future analyses because we predicted it may influence children's participation with electronic books. In addition, there were no significant differences in age, gender, parent education, or vocabulary level for children with or without prior e-book experience. There were also no significant condition differences in the number of hours per week spent with either type of book, video and television, or apps and games.

Analysis Strategy

Analyses are reported in two main sections: parent and child behaviors during reading (hypotheses 1 through 2b) and child learning (hypothesis 3). Since vocabulary and duration of prior media exposure were similar across conditions, these variables were not included in future analyses. However, age and e-book exposure (as a dichotomous code) were retained, despite being similar across groups, because they were of interest as potentially predictive of children's reading behavior and learning. We chose to use linear mixed models because they are well-suited to model repeated measures data and allow for maximum participant retention in the case of a missing data point (Cnaan et al., 1997). As such, the outcome measures that follow were analyzed using a linear mixed model with compound symmetry with book content (farm, wild animals) as a repeated effect and fixed effects for book format (print, electronic), prior book exposure, and age. Our specified model also included a fixed effect for the interaction between book format and prior book experience, as it was important to testing our hypotheses. In addition, we included a fixed effect for the interaction between book format and book content because children may become more responsive to books when they are re-read (Fletcher and Jean-Francois, 1998). Thus we believed there may be an effect of both familiar content and familiarity with the device that should be controlled for in the model. The duration of time spent reading was included in the model as a time-varying covariate except when it was the outcome. Due to the large number of statistical results generated by these models, effects relevant to our hypotheses and discussion are reported in the text; full reporting of the results including the control variables (content, duration, age) can be found in the Supplementary Tables 1–7 and an overview of group differences in outcomes is presented in Supplementary Figure 1.

Parent and Child Behaviors during Reading

Duration

Parent–child pairs spent almost twice as much time reading the electronic books than the print format books, $F(1,88.44) = 74.70$, $p < 0.001$ (electronic $M = 3{:}35$, $SD = 0{:}49$; print $M = 1{:}54$, $SD = 0{:}55$). Because of the large differences in duration spent reading due to our main variable of interest (book format) we control for duration in all subsequent models.

Hypothesis 1: Parent Non-verbal and Verbal Behaviors

Consistent with our hypothesis, parents pointed more when reading print books than electronic books, $F(1,118.80) = 15.40$, $p < 0.001$ (electronic $M = 11.80$, $SD = 11.02$, print $M = 19.38$, $SD = 13.87$; **Table 1**).

Contrary to our hypothesis, there was no significant effect of format on the number of parents' content-related utterances (excluding reading the text). Parents read more of the text from the page when they were reading print format books, $F(1,125.51) = 20.54$, $p < 0.001$ (electronic $M = 6.28$ utterances, $SD = 5.93$; print $M = 14.61$, $SD = 4.59$).

Also in contrast to our hypothesis and what has been found with older children, there were no significant medium-based differences in parents' discussion of behaviors related to reading or off-topic talk. We also saw no difference in parent page turns.

Hypothesis 2a: Child Verbal and Non-verbal Behaviors

Contrary to our prediction, children who were read the electronic books tended toward more pointing than those who read the print books, although this did not reach significance, $F(1,115.13) = 3.62$, $p = 0.060$ (electronic $M = 4.62$, $SD = 4.24$; print $M = 1.58$, $SD = 2.58$; **Table 2**). They also produced significantly more self-initiated content-related comments when being read the electronic format books, $F(1,125.03) = 6.97$, $p = 0.009$ (electronic $M = 5.46$, $SD = 4.85$, print $M = 2.13$, $SD = 2.54$). There were no significant predictors for the number of times children responded to their parent.

Consistent with hypothesis 2, there was no difference in children's off-topic talk (about snacks, flipping light switches, etc.) when reading electronic or print books. After adjusting for covariates, our model indicated that children produced more behavior-related talk when reading the print format books, $F(1,123.19) = 3.61$, $p = 0.060$, but this did not reach a standard level of significance, and the unadjusted means did not display this pattern (electronic $M = 0.81$, $SD = 2.26$, print $M = 0.59$, $SD = 1.16$).

Also consistent with hypothesis 2, we found a significant interaction between prior experience and child language. Children with no prior experience with e-books made more comments when reading electronic books, $F(1,95.76) = 3.96$, $p = 0.049$ (without experience: $M = 6.13$, $SD = 5.11$; with experience: $M = 3.77$, $SD = 3.83$).

We were unable to make any direct predictions about children's page turns based on prior literature. According to our observations, children reading the electronic book turned more pages $F(1,117.27) = 4.42$, $p = 0.038$ (electronic $M = 4.09$, $SD = 3.38$; print $M = 2.35$, $SD = 2.68$), than children who read the print books, even after controlling for reading duration.

TABLE 1 | Unadjusted means and parameter significance for parent behaviors.

Fixed effects	Electronic		Print		Parameter significance	
	M	*SD*	*M*	*SD*	*F*	*p*
Points	11.80	11.02	19.38	13.87	15.40	<0.001***
Content-related utterances	41.92	15.21	24.89	13.97	1.78	0.185
Reading utterances	6.28	5.93	14.61	4.59	20.54	<0.001***
Behavior-related utterances	4.37	4.06	1.90	2.46	0.13	0.716
Off-topic utterances	9.12	7.83	4.72	6.00	0.56	0.457
Page turns	5.98	3.65	5.62	2.56	0.75	0.390

$^{*}p < 0.05$, $^{**}p < 0.01$, $^{***}p < 0.001$.

TABLE 2 | Unadjusted means and parameter significance for child behaviors and engagement.

Fixed effects	Electronic		Print		Parameter significance	
	M	*SD*	*M*	*SD*	*F*	*P*
Points	4.62	4.24	1.58	2.58	3.62	0.060
Content-related comments	5.46	4.85	2.13	2.54	6.97	0.009**
Content-related responses	7.92	5.91	6.18	5.65	0.96	0.330
Off-topic utterances	3.74	4.28	2.50	3.63	0.76	0.386
Behavior-related utterances	0.81	2.26	0.59	1.16	3.61	0.060
Page turns	4.09	3.38	2.35	2.68	4.42	0.038*
Attention (%)	91.15	9.72	82.62	21.03	21.78	<0.001***
Availability for reading (max 5)	4.60	0.56	4.13	1.08	17.60	<0.001***
Positive affect (max 5)	3.53	0.45	3.29	0.53	12.85	<0.001***
Participation (max 5)	3.35	0.85	3.27	1.07	1.32	0.253

$^{*}p < 0.05$, $^{**}p < 0.01$, $^{***}p < 0.001$.

Hypothesis 2b: Children's Attention and Engagement

Consistent with our hypothesis, children's overall attention was significantly higher to the electronic format, $F(1,120.95) = 21.78$, $p < 0.001$ (electronic $M = 91.15\%$, $SD = 9.72\%$, print $M = 0.62\%$, $SD = 21.03\%$; **Table 2**), even after controlling for the extended duration of the electronic reading sessions.

Also consistent with our hypothesis, children made themselves significantly more available for reading (present and attending) when they were read the electronic than the print-format book, $F(1,116.10) = 17.60$, $p < 0.001$ (electronic $M = 4.60$, $SD = 0.56$, print $M = 4.13$, $SD = 1.08$), and had significantly higher levels of positive affect when reading the electronic book, $F(1,113.78) = 12.85$, $p < 0.001$ (electronic $M = 3.53$, $SD = 0.45$, print $M = 3.29$, $SD = 0.53$). There was no significant effect of book format (electronic, print) on the global measure of participation.

Hypothesis 3: Children's Learning

To determine if children were more likely to learn animal names when participating in different conditions, we ran generalized estimating equations (GEEs) using a binomial distribution with a logit link function. In these models, choices on the test trials (using screenshots from the book, photographs of the animal, and replica animals) served as the repeated effect; age, book format, performance on the familiar animal trials (as a proxy for children's understanding of and cooperation with the testing procedure) and prior experience served as fixed effects. We also included the interaction between book format and prior experience with e-books as a fixed effect. In these models we used an autoregressive covariance structure as we expected that as the test items became less similar to the learning situation, the correlation between measurements may decrease. Main effects of condition are reported here; more details are available in the Supplementary Table 8.

In the first model we also controlled for the duration spent reading the wild book (to control for the time children were exposed to the new animals). Because of the reading duration variable, this model could not include the control groups (who did not read). There was a main effect of book format, Wald χ^2 (df = 1) = 7.36, $p = 0.007$ in the opposite direction of our prediction. Children who read the e-book made more correct choices [electronic $M = 1.93$ (of 3), $SD = 0.88$; print $M = 1.28$, $SD = 1.07$; **Table 3**]. This corresponds to a medium to large effect,

TABLE 3 | Unadjusted means for learning outcomes.

	Electronic		Print		Effect size
Correct choices (of 3)	*M*	*SD*	*M*	*SD*	*d*
Experimental	1.93	0.88	1.28	1.07	0.66
Control	1.30	1.16	1.36	1.29	–0.05

Effect size computed for electronic versus print comparison. $^{*}p < 0.05$, $^{**}p < 0.01$, $^{***}p < 0.001$.

$d = 0.66$. Also in contrast to our hypothesis, there was no prior experience by format interaction.

Finally, to test whether children in the experimental conditions outscored children in the control conditions, we removed reading duration from the model. The resulting model contained only 21 control children (10 electronic, 11 print; see Test Items) and thus was very underpowered to detect condition differences. The resulting model had poor model fit (a change in QICC from 141.32 to 233.86, lower is better) and returned no significant effects (see Supplementary Table 8). The effect size for the comparison of total correct unfamiliar animal choices between control and experimental groups was $d = 0.22$ overall. However, as can be seen in **Table 3**, this effect is dampened by a lack of learning in the experimental print group. The effect size between the electronic groups alone is a moderate $d = 0.61$. With such a practically significant effect size, we do not believe it is appropriate to draw strong conclusions from the lack of statistical significance in the poorly fitting, underpowered model.

Mediation

According to Fritz and MacKinnon (2007) our sample of children used in the learning analyses (20 who read e-books, 22 who read print books) would give us adequate (0.8) power to test mediation only when there were large correlations (0.59) between both the predictor (book type) and mediator and between the mediator and the outcome (learning). Initial correlation analysis indicated that the only two predictors that even approached this criterion (with correlations larger than 0.3) were availability for reading and attention to the book. Thus, we tested these two variables for mediation using Hayes' PROCESS macro[4]. Both mediation models were run using only data from the wild animal book (from which the unfamiliar target was chosen) and included children's age and the duration spent reading as control variables.

The relationship between book format and learning was mediated by children's availability for reading. Children who read the e-book were more available for reading, $b = -1.0126$, $SE = 0.4931$, $p = 0.0495$. Availability for reading was a marginally significant predictor for learning, $b = 0.4248$, $SE = 0.2110$, $p = 0.0542$. A model with book format, availability, age, and duration as predictors accounted for approximately 25% of the variance in learning ($R^2 = 0.2529$). Bootstrapping with 5000 samples estimated the indirect effect of book format on learning through availability was significant at the 95% confidence level, $b = -0.4301$, $SE = 0.2645$, CI = −1.1154, −0.0343, supporting the mediational hypothesis.

Similar results emerged when attention was used as the mediator, measured by the percentage of time children spent with their visual focus on the book. Book format was a significant predictor of attention, $b = -0.2636$, $SE = 0.1029$, $p = 0.0166$; and attention was a significant predictor of learning, $b = 2.3709$, $SE = 1.0839$, $p = 0.0383$. Approximately 29% of the variance in learning was accounted for by the predictors ($R^2 = 0.2863$). Bootstrapping with 5000 samples estimated the indirect effect was significant at the 95% confidence level, $b = -0.6249$, $SE = 0.3781$, CI = −1.5675, −0.0291, supporting the mediational hypothesis.

In both models, book format was no longer a significant predictor of learning after controlling for the mediator (and age and duration), consistent with full mediation (availability: $b = -0.4897$, $SE = 0.5907$, $p = 0.4143$; attention: $b = -0.4663$, $SE = 0.6364$, $p = 0.4706$). However, due to our low power, the null effect supporting full mediation should be interpreted with caution.

[4]http://processmacro.org/download.html

DISCUSSION

In this study, we report differences in parent–child talk and behavior when reading print versus electronic versions of the same books. Children and parents spent twice as much time with the electronic versions of the books in comparison to the traditional print versions. After controlling for this time difference, there was no difference in parents' content-related, behavioral, or off-topic talk. Thus, contrary to our first hypothesis, and in contrast to prior studies that have been conducted with older children (Chiong et al., 2012; Parish-Morris et al., 2013; Krcmar and Cingel, 2014), parent language did not show the same bias toward behavioral talk when reading electronic books with this younger group. This could be due in part to the simple nature of our electronic books (there were no hotspots for pairs to talk about activating), or the younger age of our children. The only medium-related differences in parental behavior observed were a higher number of utterances dedicated to reading the text with print books, which may be expected due to the automatic narration of the electronic book, and a higher number of parent points to the printed book. This final observation was consistent with our hypothesis and aligns with the parent self-report of higher pointing with print in Strouse and Ganea's (2017a) survey.

We hypothesized that we would also see less pointing to the electronic book by children, perhaps due to increased touching and control of the device and thus less need to gesture. However, this was not the case; there was a trend in the opposite direction. In addition we observed higher levels of child-initiated content-related comments during the electronic book. Taken together, it appeared that children were very communicative regarding the electronic books, indicating an interest in their content and a desire to share this interest.

We expected overall engagement and positive affect with the electronic books to be higher than with print. Indeed, children paid more attention, displayed more positive affect, and made themselves more available when reading the electronic than the traditional print versions of the books. This is consistent with findings in studies with preschoolers (Moody et al., 2010; Chiong et al., 2012). The emotional quality of the reading interaction and children's attention and engagement have been linked to future reading motivation and emergent literacy skills (Laakso et al., 1999; Sonnenschein and Munsterman, 2002; Bingham, 2007), suggesting that engagement is an extremely important factor in creating developmentally supportive reading experiences. This, combined with children's commenting on the book and participation through pointing and page turns, suggests that electronic reading could be a supportive early literacy activity for toddlers, as it is for preschoolers (Takacs et al., 2015).

Contrary to our hypotheses, but adding support to the argument that electronic books support literacy development, children correctly chose a previously unfamiliar animal labeled in the book more often when they had read the electronic than the traditional print book, after controlling for the duration of the reading session. Availability for reading and attention to the book acted as mediators in predicting children's word learning at test, suggesting that electronic books supported children's learning by way of increasing their engagement and attention. The current study more accurately reflects children's typical e-book usage than Strouse and Ganea's (2017b) word learning study by using a commercially available book and having parents rather than researchers read with children. In their study, the scripted interaction was so heavily controlled by the researchers that natural differences in child attention may not have been able to emerge. The current study suggests that children's attention and engagement plays an important role in supporting learning from electronic books.

One important factor that must be considered alongside our results is the type of electronic enhancements used in our e-book. The type of multimedia enhancements used may afford different parent and child talk. Our e-book did not incorporate any hotspots for children and parents to activate, which may have partially accounted for low levels of behavioral talk. Chiong et al. (2012) reported that they did not see the same focus on behavioral talk when parents and children were reading plain e-books without enhancements that they did when pairs read books with many hotspots. Similarly, Moody et al. (2010) reported that when the number of hotspots children could activate was restricted that children produced more labels for the items on-screen. As such, the lack of a behavioral focus on the part of our participants is consistent with prior research. However, Krcmar and Cingel (2014) used very simple e-books without enhancements and still reported more behavioral talk when parents read e-books. One possibility is that the simple animations and sound effects present in our stories were well-enough aligned with the content to direct children and parent's focus on the relevant content of the book. A similar enhancement was reported to maintain the interest of 5-year-olds (Verhallen and Bus, 2009).

Electronic books may also afford different non-verbal behaviors than print. Electronic page turns may be less physically demanding for young children because they require a simple tap rather than a coordinated finger-hand-arm movement. In particular, in our book page turns could be triggered by a tap anywhere on the screen. In addition, allowing children to physically control the book by turning the pages has been suggested as a tool for teaching children the "rules" of reading as part of their developing concept of print (e.g., holding the book upright, reading right to left) (Goodsitt et al., 1988). Children in our study had more prior experience with print than electronic books. As such, it is not surprising that we saw fewer page turns in our print conditions, as children's concept of print was likely more developed for this medium.

Pointing was marginally more common from children in the electronic conditions and significantly more common from parents in the print conditions. Pointing on the part of the child has been argued to be a communicative behavior in which children direct their parent's attention or request a label (Murphy, 1978; DeLoache and DeMendoza, 1987), and thus could be indicative of children's overall engagement with the electronic book. Pointing on the part of the parent has been interpreted as more of a redirection strategy when children have lost attention to the content (Sénéchal et al., 1995), and thus could be indicative of overall lower levels of engagement with the traditional print-format books. In our case, parent pointing to print books did not engage children enough to make attention levels comparable to those with the electronic books.

Besides simple format-based differences, we also found that children with no prior electronic book experience made more content-related comments when reading electronic books than children with prior experience. Krcmar and Cingel (2014) hypothesized that children with experience invested less mental effort in processing the stories because they viewed electronic devices as toys rather than learning tools. They did not report whether parent–child talk in their study differed based on experience, but considering that content-related talk has been associated with comprehension gains from video storybooks (Strouse et al., 2013), increased content-related talk with the e-books could have been one mechanism by which children with lower prior experience could have comprehended their story better. In our study, we did not report a similar effect of prior experience on learning. This may a result of our younger sample, different learning outcome, non-narrative book or other factors. Our sample for the learning analyses was also somewhat limited in size. Future research should probe the relationship between experience, mental effort, behavior, and learning. If experience does lead to lower mental investment and learning, this may become more of an issue as tablet devices become more ubiquitous.

An important limitation to this study is the drop in power we experienced when testing our learning outcomes because of the number of children already familiar with some of the test animals. As a result, we did not have the ability to test the mediating role of parent–child behaviors on learning other than the availability and attention variables. There is a robust literature on parent–child interaction and language and literacy outcomes in preschoolers, but there is very little evidence-based information available about what constitutes high-quality language and actions during reading with toddlers and infants. It is important that before we make value judgments about whether particular formats are supportive of parent–child interaction that we have more information about what exactly high quality parent–child interaction looks like with this age group.

One important caveat to our findings is that increased engagement does not always translate into increased learning. Labbo and Kuhn (2000) called enhancements "considerate" if they relate to the story and give children more detail or information about the story content. "Inconsiderate" enhancements contain extra sounds, animations, or other features that are unrelated to the content and do not assist children in remembering the story. Considerate enhancements have been argued to be particularly supportive of literacy (Labbo and Kuhn, 2000; Turbill, 2001) and used to explain why some studies of electronic books show greater benefits than others (Zucker et al., 2009; Takacs et al., 2015). Thus, while electronic books have the potential to be supportive of language development, certain attributes may make them less effective.

Here, engagement mediated the relationship between book format and learning, but in books of other types or with other learning goals, this may not be the case. Electronic books designed to be interactive through extensive hotspots may have very different story formats and illustrations. Bells and whistles in electronic books can be designed in many ways that may increase children's participation with them, but if these features do not draw attention to the educational content they may not serve as a supportive feature. For example, Willoughby et al. (2015) reported that 3- and 4-year-olds given the opportunity to interact with electronic alphabet books at school spent more time with them than children who were given print books, but this increased time did not translate to better letter knowledge at post-test. They hypothesized this was likely because children spent their time activating hotspots irrelevant to the letter names or sounds. In addition, experiences activating built-in features that act as entertainment may heighten any tendencies children have to interpret electronic media as games rather than learning tools.

Despite this caveat, it is possible that toddler's content learning may not suffer from electronic books to the same extent as preschoolers' learning because toddlers' books tend to present stand-alone content on each page rather than narrative-based stories. As such, distractions from the content may be less disruptive because children do not need to weave together information across pages. Toddlers may also be used to behavior-related distractions from reading, as book handling is a relatively common part of the reading process at this age. Based on the positive engagement and content-related language we saw in our electronic book group, infants' and toddlers' learning from electronic books deserves further study.

Another important limitation of our study is that parent and child behavior in this lab-based observation did not match the behavior reported by parents as typical of their home behavior in Strouse and Ganea's (2017a) survey. Future research will need to explore whether these differences are due to the location of testing, the type of book read, a mismatch between parent perception and actual behavior, or other factors. Future research should also include samples with a wider variety of socio-economic backgrounds.

In sum, this work extends the prior literature by providing information about toddler–parent experiences reading in different formats. When compared with prior literature it reveals potentially significant age-related differences in the way parents treat digital formats and suggests that much more work is needed to determine the potential benefits and hazards of new media.

AUTHOR CONTRIBUTIONS

GS developed the study materials and procedures, collected the data, oversaw the transcription and coding of data, analyzed and interpreted the data, and wrote the manuscript. PG provided guidance in the development of the project and edited the manuscript.

FUNDING

This research was supported by an Insight Development Grant, 430-2014-00431 and an Insight Grant, 435-2017-0631, from the Social Sciences and Humanities Research Council, Government of Canada.

ACKNOWLEDGMENTS

Thank you to the families who participated in the research; to Heidi Xin Yi Kuang, M. E. Leroy, Elvana Xhakollari, Bethany Young, Paula Rico, Savannah Barker, Irina Kaliazine, Victoria Shirriff, and Bacibel Vasquez, for data transcribing and coding; and to Ruth Lee, Begum Özdemir, Angela Nyhout, and others in the Language and Learning Lab for helpful feedback during design of the study and manuscript preparation.

SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: http://journal.frontiersin.org/article/10.3389/fpsyg.2017.00677/full#supplementary-material

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Conflict of Interest Statement: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

ORIGINAL RESEARCH
published: 05 May 2017
doi: 10.3389/fpsyg.2017.00660

Improving Learning Outcomes: The iPad and Preschool Children with Disabilities

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The digital age has reached early childhood, and the use of touch screens by young children is common place. Research on the use of touch screen tablets with young children is becoming more prevalent; however, less information is available on the use of touch screen tablets to support young children with disabilities. Touch screen tablets may offer possibilities to preschool children with disabilities to participate in learning in a digital way. The iPad provides easy interaction on the touch screen and access to a multitude of engaging early learning applications. This paper summarizes a pilot study with 8 young children with disabilities included in a preschool classroom, who were given iPads to use in class and at home for a period of 21 weeks. Systematic observations, classroom assessments, and teacher and parent interviews documented the improvements in learning outcomes for each child in many areas including, but not limited to: shape and color recognition, letter recognition, and tracing letters throughout six research cycles.

Keywords: iPads, preschool, disabilities, tablets, touch screen

OPEN ACCESS

Edited by:
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Reviewed by:
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Specialty section:
This article was submitted to Developmental Psychology, a section of the journal Frontiers in Psychology

Received: *09 July 2016*
Accepted: *12 April 2017*
Published: *05 May 2017*

Citation:
Chmiliar L (2017) Improving Learning Outcomes: The iPad and Preschool Children with Disabilities. Front. Psychol. 8:660. doi: 10.3389/fpsyg.2017.00660

INTRODUCTION

The digital age is upon us, and with ownership of mobile devices increasing in families, many young children now have access to the use of use touch screen tablets. There is considerable debate in the mainstream media as to whether or not young children benefit from the use of these technologies, or whether these devices are harmful. Research on the use of mobile devices with young children is growing, but information on how to use these devices with young children with disabilities is still relatively scarce. Touch screen tablets offer possibilities to preschool children with disabilities such as the ability to explore learning in a digital way. The iPad provides easy interaction on the touch screen and access to a multitude of intuitive, engaging learning applications. The cognitive ability required to use this technology is substantially lower than for traditional digital technologies and even young children with disabilities can learn how to use this tool quite quickly (Chmiliar, 2013). This paper summarizes a pilot study that examined the use of iPads by eight preschool children with a range of disabilities included in a preschool classroom. The children received iPads to use at school and a home for a period of 21 weeks. This qualitative research study documented the learning each child demonstrated at home and at school; parent and teacher perceptions of the use of the iPad by each child; the use of the iPad in the classroom; and the supports that the parents and educators needed to use the iPad effectively.

A number of studies in the literature have indicated that the use of computer technologies with young children can be beneficial and can provide children with an opportunity to learn and practice skills in an engaging and interactive environment. Roschelle et al. (2000) found that the use of computer-based technologies can be very simulating and motivating for young children. Hitchcock and Noonan (2000) found that computer assisted instruction of early academic skills was successful in improving skills. Johnson et al. (2010) studied 180 preschool and kindergarten children and reported positive changes in skills when using a computer-assisted instruction, particularly with linear sequenced materials. Li and Atkins (2004) reported that early computer exposure during preschool years was associated with the development of concepts and cognition. Children who use computers have been found to show greater gains in intelligence, structural knowledge, problem solving, and language skills compared with those who do not use technology in their learning (Clements and Samara, 2003; Swaminathan and Wright, 2003; Vernadakis et al., 2005).

Research on newer technologies such as iPods and iPad with preschool children has emerged. A number of these studies have looked at the use of these devices to promote literacy skills. Dobler (2012) in classroom of first graders observed that young children were able to successfully work together for literacy practice with limited teacher assistance. Beschorner and Hutchison (2013) used six iPads in two preschool classrooms of 4- and 5-year-old children over a 7-week period of time. Apps focused on classroom skills were loaded on the iPads biweekly. They found that the children could navigate and use the iPads independently. They also observed that the children developed emergent literacy skills using the device. Students could manipulate magnet letters to write their and their friends names and several students could identify letters and use the keyboard to write simple stories and books. In a case study of two preschool classrooms with 3–5years old, Flewitt et al. (2014) looked at the use of iPads for literacy activities. Their results demonstrated that literacy activities on the iPad stimulated children's motivation and concentration. The preschool staff-recognized the potential for learning with the iPads and observed increased concentration in task completion, and enhanced communication and collaboration. Wong (2015), in a year-long qualitative study with 3–5 years old, found that young children can use iPads to communicate and learn. Children in the study were observed to gain literacy knowledge.

There have been several studies that explored the use of iPads for drawing and printing with preschool children. Couse and Chen (2010) explored the viability of tablet computers in early education, by investigating preschool children's ease in acclimating to tablet technology and its effectiveness in engaging them to draw. A total of 41 3- to 6-year-old children were videotaped while they used the tablets. The study found significant differences in level of tablet use between sessions. The teachers reported high child interest in the task and the drawings produced by the children were typical to above expectation. Matthews and Seow (2007), in a small descriptive study, looked at the symbolic representation of 12 children ages 2–11 years using electronic paint on tablet computers. The researchers videotaped children drawing with both tablet computers and traditional media. Although they reported similarities in the children's drawings using both types of media, they found that the tablet and stylus-interfaced technology was a superior tool for drawing. Patchan and Puranik (2016) looked at the use of iPads to teach preschool children how to write letters. They found that the haptic feedback provided by using a finger on the iPad to write letters helped young children learn how to write. They noted that using a finger was better than a stylus.

The use of iPads for play has also been explored with young children. Verenikina and Kervin (2011) looked at the potential for digitally mediated imaginative play with the iPad. They conducted case studies of three families with preschool children and found that the children were able to engage in imaginative play on the iPad. Murdock et al. (2013) examined the use of an app on the iPad to improve play. Three of the four children in the study demonstrated moderate and sustained improvements in play dialog that was independently generated.

Several studies have examined the used of the iPad into the everyday activities of the preschool classroom. Clark and Abbott (2016) looked at how the iPads impacted learning in literacy, numeracy and learning skills in a primary school. Improvements and greater readiness in the student's ability to learn concepts in literacy and numeracy were observed by the teacher for all students including those with lower ability and special needs. They also found that motivation, concentration and confidence grew. Another classroom-based research study (Kucirkova et al., 2014), looked at the effect of a story making app on iPads in a preschool classroom. They found that the children's engagement was higher with the story making app.

Although there is evidence in the literature regarding the use of iPads with young children, there is less information regarding the use of the iPad with young children with disabilities. Lee (2015) looked at the use of iPads in a case study of preschool children age three to five enrolled in two different preschool classrooms in a Head Start Program. A number of children had behavioral difficulties, some were English Language Learners, and several had hearing and speech impairments. The results indicated that the use of the iPad resulted in enhanced interactions between the children and the apps supported development. The children found the apps to be fun and higher levels of engagement and higher levels of motivation were reported. Another study also focused on children in Head Start programs. Brown and Harmon (2013), in a pilot study, looked at the efficacy of iPad applications in improving the literacy and overall academic skills in at-risk preschoolers. Their study included 24 children from five different Head Start classrooms. After a post-test on alphabet knowledge, matching, and number concepts, they reported that use of the iPad-supported learning in the areas of alphabet knowledge and number concepts. Zhen et al. (2015) looked at the effects of using an iPad application to teach four young children with disabilities to identify initial phonemes and found that performance was improved and the children enjoyed using the iPad. Chmiliar (2013, 2014), in a series of two pilot studies with preschool children with disabilities, found that young children between the ages of three to five were able to successfully learn to navigate the iPad. In each of the pilot studies, preschool children with a range of disabilities used iPads independently at home over an 8-week period of time. The children demonstrated improvements in many preschool skills at the conclusion of the study. For example: many of the children learned to print their name using a tracing app, several children learned to count to 100, most of the children improved their ability to complete puzzles, and one child started to talk saying words specifically related to an app about trains on the iPad. Chai et al. (2015) examined the use of an iPad application with children with developmental delays to teach early literacy skills. They found that all of the students were able to learn the target phonemes and were able to generalize the skills across materials.

Several studies were found that looked at the use of iPads with young children with autism. Vandermeer et al. (2012) examined the use of social stories on the iPad to increase on-task behavior and attention with one 5-year-old girl with autism. The child demonstrated an interest in using the iPad and an increase in attention at the end of the study. Kemp et al. (2016) found that two young children with autism spectrum disorders were better engaged in media with iPad apps than with picture books. Other studies focused primarily on the use of the iPad to promote language. Ganz et al. (2013) in a study of three children ages three to four with autism, looked at the use of a picture exchange communication system (PECS) on the iPad compared to a traditional PECS. The PECS on iPad was as effective as the traditional picture system, and two of the three children preferred to use the app system on the iPad instead of the traditional PECS. Lorah et al. (2014) looked at sentence frame discrimination using the iPad with young children with developmental disabilities and autism spectrum disorder. They had success training students to use the iPads as a speech generating device for labeling. King et al. (2014) evaluated the use of the iPad in the acquisition of requesting skills for children with Autism Spectrum Disorder. Their results showed that training with device was effective for this purpose. Still another study (Waddington et al., 2014), found that three young children with autism spectrum disorder learned to perform a three-step communication sequence using an iPad.

The last decade has seen a dramatic increase in the availability touch devices such as the iPad in homes and schools that are readily accessible to even very young children. There has been considerable discussion in the media as to the value of these technologies for play and learning and as school programs that provide support to preschool children with disabilities and their families are considering the iPad as a possible tool for learning, further information on the effectiveness of this tool is required. There is a need to better understand the role of this and other touch-screen technologies in pre-school contexts and their implications for play and learning. This research study seeks to add to the available information through a systematic look at the use of iPads with eight preschool children included in a preschool program and the learning that the children demonstrated.

MATERIALS AND METHODS

The central question for the research was: What improvements in early learning skills will preschool children with disabilities in an inclusive school program evidence while using the iPad loaded with early learning apps over a period of 21 weeks? An additional question was explored:

What support is required by the teacher and families to use this tool? The research took place in an inclusive preschool program with eight preschool children ages three to five identified as having significant disabilities. All eight children were all receiving special funding as the result of identified severe learning challenge(s). Each child in the study had the iPad to use at home throughout the study and were required to bring the iPad into the classroom each day. iPads were chosen for this study for several reasons. First, there was quick and easy access to eight iPads for the study. Second, the teacher expressed an interest in learning more about implementing iPads in the classroom and had some experience in the area. Finally, the range and number of early learning apps suitable for this research and available for use on the iPads far exceeded what was available on other mobile tablet devices that were considered.

This study used a mixed-method approach. First, this study can be seen as participatory action research. The research was an interactive inquiry process between the classroom teacher and the researchers to understand the learning that the children demonstrate, how to best implement this technology and the early learning applications in the early intervention environment, and how to effectively monitor the progress the children were making using the applications. There were 6 action cycles over a period of 21 weeks in this research. In Cycle I the teacher, children, and parents were introduced to the tool. This phase was 1 week in duration. In each of the remaining cycles, each cycle focused on a specific area of preschool readiness, and each cycle lasted 4 weeks. The five focus areas were: Cycle 2 play, drawing, tracing, and creating; Cycle 3 fine motor, tracing, and printing; Cycle 4 concepts color and shapes; Cycle 5 counting, number recognition, and number concept; and Cycle 6 alphabet recognition, letter sounds, printing letters, and early literacy.

The research followed the following procedure. At the beginning of each cycle, the research members reviewed each child's progress on the iPad and how the iPads were implemented in the classroom. They then planned the course of action for the next 4-week cycle and identified which early learning applications would be used, specific to the focus of the cycle. 6–10 apps were loaded onto each iPad. These apps ranged from simple activities that focused on the skills for the cycle that would be easy for the children to engage with, to more advanced apps that would extend their skills in that specific area. Apps related to the previous cycle were also removed at that time. Before each child received the newly loaded iPad, an informal criterion-based assessment based on the skills related to the focus of the cycle was completed. This assessment focused on the skills in that specific cycle. For example, prior to beginning the cycle that focused on the concepts of shapes and colors, each child's receptive and expressive knowledge of all of the shapes and colors that would be covered was assessed in a one–one session. Each child was then introduced to the apps for the cycle where the children were encouraged to open and try each app for a few minutes. The children then had the iPad to use at home and at school. Student use of the iPads and apps was observed three times a week a school throughout each cycle. The students used the iPads in a learning center at preschool during play time. At the end of the cycle, each child's learning related to the cycle was reassessed using the same informal criterion-based assessment and the team used information gathered in the cycle to assist in the planning of the next cycle.

Second, this study utilized a multiple case study design. Multiple-case design, or collective case design, refers to case study research in which a number of instrumental bounded cases are selected to develop a more in-depth understanding of the phenomena than a single case can provide (Chmiliar, 2010). The unit of analysis in this multiple-case approach was each student participating in the study. As the purpose of each case study was to gather comprehensive, systematic, and in-depth information about each case, each case included: pre and post semi structured interview data with parents and teacher; observations of each child using the iPad in the classroom three times a week; and informal criterion-based classroom assessments before and after each cycle. The data was organized into a comprehensive description that includes all of the major information that was then edited, parts fitted together, and organized topically. Each individual case study consists of a description of the child's experiences with the iPad focusing on the child's improvements in learning that were demonstrated throughout the research and the challenges that were faced and overcome. Finally, the case studies were integrated across cases, exploring the common threads and differences between the children. A description of parent and teacher feedback is also provided. Patterns in the data were compared between the observations by the researcher and assistant of each child in the classroom, the informal criterion-based assessment results, teacher observations in the classroom, and parent observations at home. If an observation or pattern occurred in two or more of the data collection methods it was considered to be reliable.

RESULTS

Student Data

The results begin with a case description developed for each child participating in the study. The description of each child focuses on key improvements in learning that were identified and challenges that were overcome derived from the weekly observations, data from the pre and post informal criterion-referenced assessments, and interview data from parent and teacher interviews. These results are summarized in **Table 1** Student Description.

Child 1 was a 5-year-old boy with difficulties in: speech and language; social interaction; inappropriate behavior when asked to do something and during transitions; play skills; and attention. This child exhibited many improvements in learning during all cycles of the research. Child 1 enjoyed the play house app and was observed to make up story lines, plan different activities, and started to verbalize conversations. This type of play was not seen during classroom play time. Child 1 created pictures on the iPad with careful selection of colors and content while he continued to just scribble with crayons and paper. He demonstrated substantial improvement in his ability to trace letters and print his name, learned all of the colors and shapes, and learned to count and recognize numbers. Despite the fact that Child 1 has difficulties with attention, he was able to sustain attention on learning activities on the iPad much longer than in the classroom situation. An increase in verbalizations and self-talk were observed as he used the iPad. Unfortunately, Child 1 experienced several health issues and could not complete the research. In an interview with Child 1's mother, she indicated that the iPad was very useful at home. He used all of the apps independently at home, was very willing to share use of the iPad and show what he was working on, problem solved, and focused for longer periods of time. The mother felt that her child had made huge progress with speech and language with the iPad, and he was now printing letters and his name on the chalkboard at home. In addition, the mother felt that the use of the iPad for toilet training at home was very helpful, as he was very motivated to use the toilet and have the iPad activities as a reward. However, mother reported that Child 1 was very attached to his iPad and it was difficult for her to limit the use of the iPad, particularly since the substantial learning the child was experience was having such a positive impact on behaviors at home.

Child 2 was a 4$^1/_2$-year-old boy with difficulties in: speech and language; social interaction; inappropriate behavior; and a high level of frustration. This child also experienced many successes with the activities on the iPad. Child 2, similar to Child 1 demonstrated an improved ability to trace shapes and letters and learned to print his name in the app and on paper. Child 2 also learned to identify all of the shapes including all of the complex shapes like pentagon, semi-circle, and crescent. Child 2 really enjoyed apps where he could move letters to make works, and put words into sentences. He particularly enjoyed reading books on the iPad, following along with his finger as each word was said out loud, and saying words to himself. Similar to Child 1, Child 2 engaged on a great deal of self-talk during use of the apps on the iPad and an increase in his verbalizations was evident. Similar to Child 1, Child 2 demonstrated increased engagement with the iPad over time. Child 2's mother was very convinced that the activities on the research iPad were having a positive impact on her child's learning. She noted that Child 2 was verbally repeating the letters, sounds, words, and even sentences when he played with the iPad, and these words and sentences had even emerged in conversations at the supper table.

Child 3 was a 3$^1/_2$-year old boy with difficulties in: speech and language; fine motor skills; social interaction; and confidence. Although Child 3 also demonstrated many learning gains throughout the research, he struggled with the iPad initially. He was reluctant to use the iPad and required direction on how to use the apps and how to use one finger to navigate and select items. Child 3 did not enjoy the fine motor apps and would only engage in an activity if the focus of the app was car or vehicle related. Toward the end of the research Child 3 started to engage with the iPad more as he found apps that appealed to him. Similar to Child 1 and Child 2, Child 3 learned to identify letters of the alphabet and huge improvement with tracing letters was observed as he went from not being able to trace at all, to tracing with relative accuracy for many letters. Child 3, like Child 1 and 2, was also observed to engage in more and more self-talk as he used the apps. He started to use a greater variety of words and sentence length also increased. In an interview with Child 3's mother, she

TABLE 1 | Description of subjects.

Child	Age	Gender	Learning difficulties	Improvements in learning	Challenges
1	5	Male	Speech and language Social interaction Behavior Play skills Attention	Dramatic play Drawing and coloring Tracing Printing name Attention to activities Language Attention Independence	Too attracted to the iPad Mother found it difficult to limit use at home
2	41/2	Male	Speech and language Social interaction Behavior Frustration	Engagement in play Tracing Printing name Concepts Letter and word recognition Language Attention Independence	Very frustrated at the beginning Wanted apps to work right away Preferred apps that related to his interests
3	3 1/2	Male	Speech and language Social interaction Confidence Fine Motor	Language Letter recognition Tracing Singing	Needed support to start using the iPad Struggled with using one finger to tap Limited interest in apps that focused on areas that did not interest him
4	4	Male	Speech and language Social interaction Confidence Attention Frustration Fine Motor	Engagement in play Language Puzzle completion Tracing letters Confidence Independence	Reluctant to engage with the device initially Avoided apps he thought were too difficult
5	5	Male	Speech and language Social interaction Behavior Attention	Play Concepts Numeracy concepts Tracing Printing his name Language Book use	Concerns that he might be just memorizing all of the app content
6	5	Female	Speech and language Attention Fine motor Impulsivity	Creativity Concepts Puzzle completion Tracing Printing Letter recognition	Cost of buying child an iPad Parents found it difficult to limit the use of the device at home
7	4	Female	Speech and language Attention Fine motor	Play Language Puzzle completion Letter identification	Difficulty at the beginning paying attention to apps
8	31/2	Male	Speech and language Fine motor skills Attention	Puzzle completion Concepts Counting Language	Struggled with finger control and accuracy initially

indicated that Child 3 did not use the research iPad at home that much as they had an iPad at home that the child preferred to use with his games and train videos on it. When Child 3 started singing at home for the first time at home, his mother indicated that he was singing songs he was playing with on the iPad. Like Child 1 and Child 2, Child 3 demonstrated increased attention with some activities on the iPad particularly when reading books on the iPad versus print.

Child 4 was a 4-year-old boy with difficulties in: speech and language; fine motor skills; confidence; social behavior; attention; and frustration. Similar to Child, Child 4 was initially reluctant to engage with the iPad. He did not like to engage with apps that he perceived to be a little difficult for him. Once the app was introduced to him and he had a chance to try it a couple of times with help he was more likely to independently choose to use the app. Initially, Child 4 was only independently using one or two apps. About half way through the research it was noted that Child 4 opened and used all of the apps. Like the previous three participants, Child 4 improved his tracing skills substantially and went from not being concerned about staying on the line to being able to trace all of the letters. Similar to Child 1, 2, and 3, Child 4 was observed to participate in increased self-talk and verbalizations as he played in the apps. In an interview with Child 4's mother, she indicated that her son was not "into the iPad at first and preferred to play outside." Her son was quite frustrated with apps that did not work immediately for him but was more confident after he played with them with his brother. She reported that at some point his use of the iPad and "his language exploded." She was convinced that he was imitating the voices in the apps. In her opinion, her child preferred apps that were related to things that he likes such as trains, trucks, and superheroes. She was quite happy that he was now using the iPad independently.

Child 5 was a 5-year-old boy with difficulties in: speech and language; social behavior; behaviors such as following directions and transitions; and attention. Similar to Child 1 and 2, Child 5 engaged in independent and appropriate digital play on the iPad although he typically did not engage in social or constructive play in class. Child 5 also made many learning gains throughout the research. Improvements in tracing and puzzle completion were observed, as well as in shape recognition, counting and number concept. Similar to the previous participants, Child 5 made significant gains in tracing letters and in letter recognition. He learned all of the letters, the sounds of the letters, and had memorized many of the sentences in the apps. And similar to the previous participants, an increase in verbalizations was observed. In an interview with both the mother and the father of Child 5, they indicated that their child had made "incredible" learning gains using the iPad. They had struggled at home to get their child to participate in any learning activities including reading stories to him. Now their son loves the book apps that tell a story and will tell the story back to them. They noted that he had learned to trace all of the letters, could count to 100, learned to write his name, and learned all the shapes. They also indicated that they felt his vocabulary had really increased.

Child 6 was a 5-year-old girl with difficulties in: speech and language; attention; fine motor; and impulsivity. Child 6 was very familiar with the iPad at the start of the study and she used the iPad in very different ways than the other children in the study. Child 6 changed the picture on her screen and every week a new creation was on display. This child created many stories, pictures, and videos independently. In addition to her creations, Child 6 was observed to make many learning gains. She demonstrated improvements in puzzle completion, shape and color recognition, and counting. Similar to the previous participants, Child 6's ability to trace letters improved. Her ability to stay on the line while tracing letters did not change, but she learned to trace the letters in correct and organized way. In an interview with Child 6's mother and father, they indicated that their daughter enjoyed using the iPad to take pictures, record her voice, and make video movies. The parents felt that she had explored all of the apps and indicated that they had observed improvements in printing, recognizing letters, counting, and puzzle completion. Unfortunately, they reported that they had difficulties getting the iPad away from her and struggled to set parameters around the iPad use. They also indicated that although they would like to purchase an iPad to continue their daughter's learning, they had concerns about the cost of the tool.

Child 7 was a 4-year-old girl with difficulties in: speech and language; attention; and fine motor skills. Similar to Child 3, 4, and 5, Child 7 needed help to get started with the iPad. Although she was interested in the iPad, all she was able to do was tap the screen over and over without even looking at what she was doing. Over time her ability to attend to learning tasks on the iPad improved substantially. Similar to the previous participants, Child 7 demonstrated a number of learning gains in many areas. Child 7 went from not being able to complete any puzzles to independently completing 32 piece interlocking puzzles. Similar to the previous participants, Child 7 made considerable gains in tracing letters and learned to print her name. She also made learning gains in recognizing colors and shapes, counting, and number recognition, letter recognition and sounds. Similar to Child 1, and 2, Child 7 demonstrated an improved ability to focus and maintain attention when working on activities. Unfortunately a parent was not available for an interview at the conclusion of the research.

The final case, Child 8 was a $3^1/_2$-year-old boy with difficulties in: speech and language; fine motor skills; and attention. Similar to Child 3, 4, and 7, Child 8 was initially a little reluctant to use the iPad at the beginning as he struggled with the fine motor apps due to very poor finger control. Child 8 demonstrated learning gains in a number of areas. He learned to independently complete 12 piece interlocking puzzles, learned to recognize a number of shapes and colors, and made significant gains in counting. Similar to the previous participants, Child 8 demonstrated an increase in verbalizations and ability to maintain attention to learning tasks. During the final interview with Child 8's mother, she indicated that they did not use the iPad that much at home, but used it a lot as they traveled in the vehicle and at hockey practice. She felt that her son really liked the action and noise in the apps and particularly enjoyed the interactive books. Similar to many of the other parents, the mother felt that the iPad use had a huge impact on her son's language. He was using a much wider range of words at home and she had noticed that he was using the same inflection in his voice as on the apps.

In summary, all of the participants in this research learned how to use the iPad independently. The majority of the eight children were able to learn how to use the iPad immediately. The other children demonstrated some reluctance initially to use the iPad because they had difficulties with fine motor skills and using their finger to touch and navigate, because they were not able to maintain attention on the screen, or because they were not interested in the content of the apps. Each of the students that demonstrated difficulties were able to overcome their difficulties in a short period of time with verbal directions, modeling, positive feedback, and practice. As the research progressed it was evident that all of the students were enjoying their learning activities on the iPad and three of the eight students were observed to be able to sustain attention in the activities for longer periods of time. All of the students demonstrated learning gains in a number of areas and all of the children demonstrated improvements in their ability to trace letters and print their name. Several of the children learned the letters of the alphabet, the sounds the letters make, some simple words, and two of the students were very interested in reading sentences on the apps. All of the children demonstrated increases in self-talk while they played, and increases in vocalizations and vocabulary were observed at school and by the parents at home. Two of the children demonstrated a range of play skills on the iPad such as creative play or construction that they were not able to demonstrate in play time in the class.

Parent Feedback

All of the parents interviewed in the study spoke positively about the iPad as a learning tool. One parent commented, "We love having the iPad. . . hugely beneficial." Another parent said, "This is a good tool. . . it is a great tool to reinforce things, it is easier to manage their learning, easier when the child thinks it is a game and they can do it themselves." Yet another parent agreed with this, "He does not think he is learning, he thinks he is playing." In one interview, a mother and father commented that the iPad, "May be better than therapy – it is play, there is no judgment, he feels included and he is using the same device as mom and dad.

During this research project, the parents were provided with different kinds of support to help them use the iPad at home with their child. At the beginning of each cycle, the parents were provided with a list of the apps that were loaded onto the iPad for their child. A brief description of each app was given. Most of the parents indicated that the newsletter was more than enough information for them and they were able to look at and understand the apps based on this information. Several parents indicated that the newsletter was not quite enough information for them to understand how all of the apps worked. In addition to the newsletters, an afternoon workshop was held for the parents to show how many of the apps worked. There was also a demonstration of how to use the apps for developing books and videos. One parent indicated that the workshop was very helpful for her and without the workshop she would most likely not have tried to create a digital story with her son although she was still working on how to do this. One parent said that the workshop was good exposure to all of the apps; otherwise she would not have looked at and tried all of the early learning apps. Many of the parents indicated that they were loading the apps used in the research onto their own devices; one mother reported that she would like to be able to buy an iPad fully loaded with all of the apps from the research study.

There were only a couple of negative comments expressed by the parents during the final interviews. One set of parents were concerned that the iPad was too expensive for them to purchase for their daughter. This was making them feel bad because they had witnessed so many learning gains when their daughter used the iPad and she liked it so much. The other comment is not so much negative as constructive. Another set of parents indicated that they would really like to see the curriculum coordinated with the apps. Although the themes of the apps and the themes for learning in the classroom were similar, they would have liked specific information as to how the apps related to classroom learning objectives and their child's individualized learning plan.

Teacher Feedback

In the final interview with the classroom teacher, she reported that she was happy with the learning that the children displayed on the iPad. She felt that learning activities on the iPad were for the most part very good and very engaging for many of the children. She was most impressed by the fact that this mode of learning ". . .seems to work for children that are difficult to reach and teach in other traditional ways." This may be because the iPad is a ". . .very powerful tool, multi-modal and attention getting."

The teacher also indicated a number of concerns with the implementation of iPads in the classroom. Her main concern was with time for planning. She felt that it took a lot of time to set up the iPad with apps and to change the apps for each cycle. A considerable amount of time was involved in finding and selecting which apps to use. There is also additional time required to determine how the apps match up with classroom goals and each individual child's learning objectives and to set up the iPad with the apps. During the research, difficulties were experienced downloading apps as there was very poor wireless access in the school. All of these issues are a concern for the teacher because time to work on the iPad was taken from planning time for other things in the classroom.

The second significant challenge for iPad implementation in the classroom was the need to monitor the use of the iPad in the classroom. The teacher felt that the use of iPads in the classroom does require supervision as she would want to know how the children were using the iPads. During the research additional staffs were available for supervision. In normal circumstances this support would not be available. A checklist with the children's names, apps, and skills was set up for the classroom learning center. This type of checklist, if used by the teacher after the research, might help her address this problem.

The teacher reported that there were a number of uses for the iPads in the classroom in her opinion. She could see the iPads best used in a play center with concept related apps similar to how the iPads were used in the research. The iPad could also be used in a therapy model and customized for each child's needs. At the conclusion of the research, the teacher could also see the importance of involving parents in the use of iPads through parent meetings where they could try different apps and see what apps they might want for their child.

DISCUSSION

Child Outcomes

Mobile devices such as the iPad have been becoming more prevalent and these devices are frequently becoming part of the early childhood experience at school and at home. In this study, it was observed that the majority of the children participating learned how to use this device quickly. This finding is consistent with the literature. Couse and Chen (2010) found that preschool children learned to use the iPad quickly and were able to explore independently. Beschorner and Hutchison (2013) observed that young children could use iPads independently with limited teacher involvement. Even young children with disabilities were able to master navigation of the iPad quickly and easily (Chmiliar, 2013, 2014). However, it was observed in this study that several children needed a little more support, direction, and time before they were willing to be fully engaged with the device. Child 3, 4, and 8 lacked the fine motor skills to correctly make choices on the iPad screen and as a result avoided using the iPad because they did not want to make errors. Once they had instruction on how to use their finger to tap and additional practice they were able to use the iPad independently. Child 7 had difficulties attending to content on the screen initially. With prompting she was able to learn how to focus on activities. It cannot be assumed that children already have the skills to use the device, and young children with disabilities who may have fine motor challenges may need additional time to learn how to navigate the device.

The literature indicates that the use of educational technologies in the classroom and at home can result in positive learning outcomes for young children (McCarrick and Li, 2007) and the use of early learning apps on the iPad can help children learn preschool children (Dobler, 2012; Chmiliar, 2013; Beschorner and Hutchison, 2013; Flewitt et al., 2014). Research supports the view that children with special needs – mobile learning can be a part of the solution that can help children with special needs to communicate and learn basic concepts (Kokkalia and Drigas, 2016). In this study, the children displayed learning gains in many areas. The learning in each cycle differed from child to child. For example, all of the children demonstrated improvements in their shape and color recognition, but several children showed substantial learning gains. Child 1 and 2 learned all of the colors and shapes including shapes not yet learned by their peers in the classroom such as crescent, pentagon, and octagon. All of the children improved in their puzzle completion skills. Child 5, 6, and 7 made huge gains in their skills. Child 7 progressed from not being able to complete a simple puzzle to being able to compute a 32 piece interlocking puzzle. All eight children made substantial gains in their letter tracing, and alphabet recognition. Child 7 learned all of the letters of the alphabet and the sounds that each letter makes. Child 5 not only learned all of the letters of the alphabet and the sounds, but also started to read simple sentences. For several children, the greatest learning occurred when there were specific apps available for them to use that appealed to their interests. For example, Child 4 made minimal learning gains in each of the cycles until the cycles on numeracy and literacy. Once he started working on the math apps that included monsters, his interest soared and his skills started to improve at a more rapid rate. Child 4's mother also indicated that in the literacy cycle her son's interest in books expanded dramatically and she observed a corresponding explosion of language development related to the books apps. To maximize the learning potential of this device, it may be advantageous to be aware of the child's interests and match the apps to the child's interests and developmental level.

One of the reasons that the use of the iPad and learning apps was so successful was that using the iPad can be fun and engaging. All of the students in this study appeared to like using the iPad and found apps that appealed to their interests. Lee (2015) reported that children in a Head Start program found use of the iPad fun and engaging which resulted in high motivation to participate. Increased learning may also be related to the fact that young children are able to use the device independently. This motivation resulted in increased concentration and persistence to tasks (Flewitt et al., 2014). The mobile applications and learning activities on them may increase children's interest during learning as a result of multimedia elements such contains multimedia elements such as animation, graphic and video encouragement (Kokkalia and Drigas, 2016). In this study, an increase in attention to tasks as the weeks progressed was observed. The children worked for longer on apps, were able to sustain attention to tasks in apps until they were successful. This was even true for children who had significant attention problems in the classroom. One of the areas that several children experienced significant success in on the iPad was with creative and imaginative play. Several children with inappropriate play skills were able to engage in imaginative play in a playhouse app that were not able to engage in this type of play during centre time in the classroom. This was particularly true for Child 1 and 5. Both children engaged in creative play on the iPad that included dressing characters up and dramatizing household activities. This finding is similar to Verenikina and Kervin (2011), who observed imaginative play when preschool children were using the iPad. Digital creative and imaginative play could become a significant part of young children's lives, and apps may be able to facilitate a learning environment for children who struggle in this area.

A second area where many improvements were observed for some children in this study was in the area of language. In the classroom, a number of children engaged in a lot of self-talk as they played with the apps, labeling items on the screen, imitating the language that they were hearing, or repeating words or phrases being read to them. It was also observed, that with apps where the children could record their own voices as part of the tasks in the app, they spent a great deal of time recording themselves over and over. For example, Child 6 recorded her voice on every item in one app, correctly identifying in a two word sentence the color of the object and the name of the object. Several parents also reported that they had witness a huge change in their child's language at home and that they were certain the change was the result of playing in the apps as the language being used was very app specific. Child 2 was reported to be repeating letters, sounds, words, and sentences at home. Child 3's mother reported that he started singing songs from the iPad for the first time. Child 4's mother reported that his language us at home "exploded." Child 5 starting telling stories back to his parents that he had read on the iPad. Child 6 narrated movies and showed them to her parents. Finally, Child 8's mother reported that his language used increased and that she observed that he was using the same voice inflection in the words as in the apps. At this point every few studies had focused on this area. Improvement in language after playing with apps on the iPad was noted by Chmiliar (2013, 2014) and Murdock et al. (2013) noted improvements in play dialogue when children played on the iPad. Flewitt et al. (2014) observed enhanced communication and collaboration when children played with the iPads in centres. This is a very important area to consider. The majority of children in this study had significant developmental delays in speech and language development and had been receiving support for this learning challenge at school from other professionals. Perhaps playing on the iPad with strategically selected apps could positively supplement speech and language programming for children with disabilities.

Although this study produced similar results to other studies in the literature focusing on the use of the iPad by preschool, this study is significantly different from the others in several ways. This research study occurred in the everyday classroom environment and in the home environments of the children. The situation was not contrived and the children interacted with the iPads as play activities with the teacher, researchers, and parents as observers. If iPads are going to be implemented effectively into preschool classrooms, then data and information gathered from studies that bridge the gap between the research environments and the classroom is very important. This study is also different from others in that multiple perspectives were used to evaluate the children's learning. The researchers carried out systematic observations and informal assessments of the children in the classroom, the parents shared their perspective and observations from the home environment, and the teacher contributed with her observations and assessment data. Contributions from multiple participants resulted in a rich data set and multiple perspectives on each child's use of the iPad and the learning that occurred

Finally, and perhaps most importantly, the purpose of this research was not to manipulate the environment to test the effectiveness of the iPad in teaching a specific concept or skill. The purpose was to facilitate access to the use of the iPads for young children with disabilities and monitor how they used the iPads and the learning that occurred. Each child could choose the apps that they wanted to engage with and they explored the apps independently in the play center at school and at home. Each child demonstrated substantial learning in one or more cycles in the research. This may be due to the interactive interface and the engaging multimedia apps that capture attention. Or it may be due to the fact that the apps chosen for each cycle were well designed and included continuous schedules of reinforcement. But, the additional element for success may be that the children had choice and control over their activities. They had the power to engage with the apps independently. Child 7 chose to learn all of the letters of the alphabet and their sounds in a 4-week cycle and chose to learn how to complete a 32 piece interlocking puzzle. Child 2 chose to learn all of the shapes and colors in every app, many of which would be considered to be difficult to learn at the preschool level. Several of the children demonstrated significant changes in the language that they were using at home because they were able to choose to imitate and verbalize sounds, words, and even sentences while playing on the iPad. Although this element needs to be explored further before conclusions can be drawn, it may be an important factor for young children with disabilities who often have few ways of having independence and control in their lives.

Teacher Outcomes

Education for teachers is required in order for this technology to reach its full potential to support learning in the classroom (McManis and Gunnewig, 2012). In this study, the teacher indicated that the amount of time spent to find apps that related to the curriculum and learning objectives for the children was substantial and that it would take away from other types of essential planning. Teachers could benefit from access to information and resources on what apps to use and how they relate to the curriculum. So much time and effort is required to select good apps in each area. Hutchison et al. (2012) supported this perspective, indicating that the learning potential of iPads is directly related to the teachers' ability to link the use of the iPads to the curriculum. It is important to ensure that apps on the iPads are used to enhance curricular integration and support identified learning goals (Northrop and Killeen, 2013).

The teacher in this study also reported the importance of being able to monitor the use of the iPads by the children in the class. McManis and Gunnewig (2012) recommend that progress monitoring is need to gather information on how children are interacting with the devices in the learning content. They recommended digital portfolios, apps with built in monitoring, and using the recording features in apps as possible tools for this purpose.

Parent Outcomes

The parents in this study reported that the monthly newsletters really helped them to understand the apps that their child was using on the iPad and many of the parents also indicated that they found the workshop very useful. One mother indicated that she would not have tried the digital storytelling app without the workshop. Several of the parents indicated that they would like to know how the apps on the iPad related to the class curriculum and learning objectives. Northrop and Killeen (2013) also found that use of the iPads provided an excellent opportunity to connect school and home-learning activities.

Several parents in this study found it difficult to manage the amount of time their child spent on the iPad. One parent was very reluctant to limit her child's access to the iPad as he was learning so many things and his in appropriate behaviors at home were reduced. The parents who set parameters around the use of the iPad at the beginning of the study reported no difficulties. These are results are similar to Verenikina and Kervin (2011) who observed that parents who predetermined and defined the use of the iPad in terms of time had children that were accepting of the limitations set by the parents. In the present study, several parents reported that their child did not use the educational activities on the research iPad very much due to the fact that another iPad or other digital media was available to the child that had preferred games and videos on it. If fun non-cognitive activities are available to the child as an alternative to educational activities—the child will choose the more preferred activities. If learning is a goal for the child, access to non-educational games and videos can be restricted to specific time such as traveling in the car, then fun engaging educational apps will be chosen more frequently.

CONCLUSION

Overall, the iPad appears to be a tool that can help to have a positive impact on young children with disabilities in the preschool inclusive classroom. iPad can be used independently by young children with disabilities and this research showed that children with disabilities can learn a range of preschool skills on the iPad. In light of these results, the iPad could be a promising tool to help preschool children with disabilities to learn skills essential in the inclusive classroom.

Although this study is helpful in illuminating the possibilities of the iPad in the inclusive preschool classroom, it has limitations. There were very few participants in this study. The eight children in the study were a very diverse group of children in terms of their ages and how their disabilities manifested in the classroom. In addition, the teacher in this study was very willing and interested in integrating the iPad into the classroom. Other early childhood teachers may not be as willing or as interested in investing the time, energy, or commitment implementation of iPads requires. The parents were also very interested in participating. This may be in part due to the fact that this preschool classroom incorporated parent involvement into their program, but this may not be the same for other classrooms. Due to the very limited scope of the study and the small number of preschool children involved, there is not yet sufficient evidence to determine the best practices of the use of this tool with this population. However, given the positive results that this study produced, the use of this device as an early learning tool for children with disabilities should be explored further.

ETHICS STATEMENT

The study was approved by Athabasca University Research Ethics Board. The teachers and parent signed a consent form after reading an information letter and discussing the research with the researcher. The parents of the children signed the consent form for their child to participate.

AUTHOR CONTRIBUTIONS

LC wrote the grant application, received the grant, set up the research, worked with the teachers, children, and parents, analyzed the data, and wrote the paper.

FUNDING

This research was funded by an Academic Research Fund Grant from Athabasca University, Athabasca, Canada.

ACKNOWLEDGMENTS

Many thanks to the early childhood classroom that allowed us to come into their classroom to conduct the research. Thank you to the teacher, parents, and children that gave us their time and were so generous in sharing their observations and perspectives and to Amanda Kolby who worked so tirelessly on the iPads and the apps. Parts of this research have been presented at the ICCHP 2016 International Conference on Computers Helping People with Special Needs, July 13–15, 2016, University of Linz, Austria. "The iPad Helping Preschool Children with Disabilities in Inclusive Classrooms."

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Conflict of Interest Statement: The author declares that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

frontiers in Psychology

ORIGINAL RESEARCH
published: 12 April 2017
doi: 10.3389/fpsyg.2017.00578

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All Tapped Out: Touchscreen Interactivity and Young Children's Word Learning

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Touchscreen devices differ from passive screen media in promoting physical interaction with events on the screen. Two studies examined how young children's screen-directed actions related to self-regulation (Study 1) and word learning (Study 2). In Study 1, 30 2-year-old children's tapping behaviors during game play were related to their self-regulation, measured using Carlson's snack task: girls and children with high self-regulation tapped significantly less during instruction portions of an app (including object labeling events) than did boys and children with low self-regulation. Older preschoolers ($N = 47$, aged 4–6 years) tapped significantly less during instruction than 2-year-olds did. Study 2 explored whether the particular way in which 170 children (2–4 years of age) interacted with a touchscreen app affected their learning of novel object labels. Conditions in which children *tapped* or *dragged* a named object to move it across the screen required different amounts of effort and focus, compared to a non-interactive (*watching*) condition. Age by sex interactions revealed a particular benefit of dragging (a motorically challenging behavior) for preschool girls' learning compared to that of boys, especially for girls older than age 2. Boys benefited more from watching than dragging. Children from low socioeconomic status families learned more object names when dragging objects versus tapping them, possibly because tapping is a prepotent response that does not require thoughtful attention. Parents and industry experts should consider age, sex, self-regulation, and the physical requirements of children's engagement with touchscreens when designing and using educational content.

Keywords: educational technology, touchscreen, app, interactive, tap, drag, haptic exploration, executive function

OPEN ACCESS

Edited by:
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Specialty section:
This article was submitted to Developmental Psychology, a section of the journal Frontiers in Psychology

Received: *21 July 2016*
Accepted: *28 March 2017*
Published: *12 April 2017*

Citation:
Russo-Johnson C, Troseth G, Duncan C and Mesghina A (2017) All Tapped Out: Touchscreen Interactivity and Young Children's Word Learning. Front. Psychol. 8:578. doi: 10.3389/fpsyg.2017.00578

INTRODUCTION

"It's already a revolution, and it's only just begun." With these words, the Apple iPad was launched on the world in 2010, a few years after families first fell in love with miniature touchscreens on their phones. Today, mainstream adoption of smartphones has permeated the socioeconomic divide in the U.S. (Smith, 2013), with most families of all income levels now having a touchscreen device. According to a 2015 study, 90% of toddlers in a low-income, traditionally underrepresented population in the U.S. had used a touchscreen by age 2, and 83% of children under 5 had a tablet computer in their home (Kabali et al., 2015). As touchscreen devices and apps (applications) quickly became a part of daily life for youth and adults, the developmental and educational effects of interactive media emerged as an important, highly debated topic. Yet research into the effectiveness of touchscreens for children's learning and their impact on family life has lagged behind (Troseth et al., 2016).

Despite the lack of research, parents and teachers avidly buy touchscreen apps. Approximately, 80% of the over 170,000 educational apps in the iTunes store (Apple, 2017) are designed for children, with toddlers and preschoolers representing the most targeted age group (Shuler, 2012). Because children are given access to touchscreens at a very young age, it is imperative to study the effects of interactive technology on children's learning and development.

Scientific investigation of screen media for children is not new. Decades of research document both positive and negative effects of exposure to children's television (see Anderson and Kirkorian, 2015, for a review). Such effects are highly dependent on the content of the media and the viewing context (i.e., viewing with or without an adult co-viewer), as well as the age of the child. Research has consistently demonstrated that young children, particularly those under 24 months of age, learn better from an individual who is with them in person rather than on a screen (Barr, 2010; Troseth, 2010). For instance, in one study, 15- to 24-month-old toddlers learned significantly fewer words from a children's television program compared to learning directly from an adult; very few children under 22 months learned any words from the TV program (Krcmar et al., 2007). The same pattern of results has been found in infants' and toddlers' problem solving and imitation of behaviors modeled on video or observed "face to face" (Troseth and DeLoache, 1998; Barr and Hayne, 1999; Schmitt and Anderson, 2002).

However, this learning difference might have less to do with the video medium than with the relatively passive nature of watching events on a TV screen (Christakis, 2014). Recent advances in technology allow viewers to actively engage with people on a screen via video chat (e.g., Skype and FaceTime). Research indicates that children as young as 24 months successfully use video as a source of information when an adult on screen interacts with them in socially contingent ways (Troseth et al., 2006; Roseberry et al., 2014; Myers et al., 2016). Thus, active engagement with a responsive on-screen partner seems effective in helping young children to learn from video.

Touchscreen devices afford a different, non-social kind of contingent interaction: physical touch leading to an on-screen response. Individual differences in motor skills, dexterity, and decision making now play a role in how a medium is experienced. Physical interactivity with the screen gives the user agency as he or she chooses and directs what happens. For example, one child may tap an object on the screen that then displays an animation; a child who does not tap the object will have a different experience. These contingent interactions can create an adaptive, scaffolded experience for the user, which is a powerful aid for learning when properly designed (Hirsh-Pasek et al., 2015). In essence, the individual child's characteristics, preferences, and actions mold the medium, within the bounds of the interactive design. Based on the idea that physical, like social, contingency will make screen media better for learning, developmental researchers are now exploring this new technology (e.g., Choi and Kirkorian, 2016).

In prior studies that are relevant to the subject of learning via touchscreen interactivity, adults and children acted on objects, or actively engaged with material on a computer, compared to merely viewing the same objects or events. Important differences in these situations include additional information available from touch compared to watching (Smith and Olkun, 2005; Bara et al., 2007; Kalenine et al., 2011; Möhring and Frick, 2013), and the fact that active engagement in an experience changes how the event is processed and remembered (James and Swain, 2011; Kaplan et al., 2012; Kersey and James, 2013). The type of interactive behavior and its temporal and spatial correspondence to on-screen events also may affect memory and learning (Sapkota et al., 2013; Schwartz and Plass, 2014; Choi and Kirkorian, 2016; Kirkorian et al., 2016).

Much early learning happens through multisensory exploration, which becomes more sophisticated and efficient across the preschool period (Thelen, 2000; Scofield et al., 2009). The combination of *visual information* and *touch* (visuo-haptic interaction) promotes young children's learning over simply watching. For example, preschoolers offered 3D shapes were more likely to manually explore the shapes and recognize them later than were children given 2D paper cutouts of the shapes (Kalenine et al., 2011). Similarly, low-SES kindergarteners who explored target letters both visually and haptically had significantly improved reading skills compared to those who only explored the letters visually (Bara et al., 2007). The same advantage of visuo-haptic exploration was found for babies: 6-month-olds *mentally* rotated objects with greater success if they first *manually* explored the objects by hand, compared to those who only observed the objects rotating (Möhring and Frick, 2013).

Carrying out actions on objects changes brain responses when perceiving the stimuli later. After physically engaging in actions with objects (versus observing someone else do the actions), children between the ages of 5 and 7 demonstrated greater neural activity in motor and sensorimotor brain areas while perceiving the stimuli (*seeing* the objects or actions, or *hearing* verbs describing the actions – James and Swain, 2011; Kersey and James, 2013).

Even indirect physical interactions with on-screen objects using a computer mouse or stylus benefit learning. In one example, 9-year-olds and college students explored a series of 2D shapes on a computer screen by either manually dragging each object with a mouse to rotate it (interactive condition) or observing the object rotate automatically. During a later test, participants in the interactive condition mentally rotated significantly more objects (Smith and Olkun, 2005). In another study, adults performed better in immediate and 3-week-delayed recall and recognition tests after they dragged target objects with a computer mouse, compared to clicking on objects that then moved automatically (Schwartz and Plass, 2014). Dragging a virtual object (e.g., an eraser, a paintbrush) in this study was an "iconic" movement related to the meaning of the to-be-learned phrase and the depicted context (e.g., *erase the blackboard*; *paint the fence*). Enacting a meaningful action promoted better memory than did clicking to produce a very similar object movement. In general, active manipulation can make an experience with digital technology "minds-on" for both adults and children, increasing their cognitive engagement and supporting learning (Hirsh-Pasek et al., 2015).

The spatial correspondence of a user's physical interaction with an on-screen object or event can also promote learning, but results with young children are not straightforward. Adults' short-term memory for stimuli improved when their touchscreen taps with a stylus corresponded with the location of the target (Sapkota et al., 2013), which directed participants' attention to the to-be-remembered information. In contrast to this clear finding, emerging research with preschool-aged children reveals an intriguing paradox. Children younger than 30 months of age reliably learned new object labels when they had to tap the on-screen box where a named target object was hidden (specific contingency), but they did not learn when they tapped elsewhere on the screen (Kirkorian et al., 2016). However, toddlers over 30 months learned better when only general tapping was required or if they simply watched events unfold; for them, the requirement to tap in the relevant spot actually detracted from learning. Choi and Kirkorian (2016) found the same results with a different learning task, except the children who were helped by specific contingency were 6 months younger than the comparable group in the previous study. Therefore, the particular kind of contingent screen interaction that aids learning may differ depending on the task and the age of the learner.

The fact that interaction can direct children's attention could be a powerful tool for learning, but it could also create distraction, depending on the design of a touchscreen activity and individual differences in children. Interactive elements such as hotspots and games appear in the majority of electronic books (e-books) that young children "read" on touchscreens, but such features often are unrelated to the story (Guernsey et al., 2012). In a recent meta-analysis, *multimedia* features (such as animations and sound effects) that directed attention to the e-book story enhanced learning, but interactive games, pop-ups, and hotspots (whether story-relevant or -irrelevant) detracted from young children's learning, especially for children from disadvantaged backgrounds (Takacs et al., 2015). Similarly, manipulative elements in print books (pull tabs, flaps, textures) have been shown to impede word learning in 20- to 36-month-old children (Chiong et al., 2010).

Two important results emerged in a recent study using a simple e-book in which a narrator labeled pictured objects (Strouse and Ganea, 2016). First, toddlers (19–23 months) learned a word when they had to tap on the object to go to the next page, but did not learn if the story progressed automatically; thus, simple, on-task interaction promoted learning. Second, children failed to learn when their touch produced a rewarding, child-friendly (but irrelevant) sound effect and animation before the page turned. Thus, even simple off-topic interactivity appeared to interfere with learning.

Why is screen interactivity such a double-edged sword for very young children? Numerous research studies indicate that young children have immature executive functions, such as the ability to focus attention and control their impulses (Carlson, 2005; Garon et al., 2008; Richter and Courage, 2017). For instance, 2- and 3-year-old children's ability to push one of two buttons to complete a spatial matching task related to measures of their inhibitory control (assessed with Kochanska's *snack delay* task), although few young 2-year-olds had sufficient inhibitory ability to complete either task (Gerardi-Caulton, 2000). In another study (Diamond and Taylor, 1996), children had to inhibit a response tendency to match an adult's behavior: if a researcher tapped a peg on the table once, the child was to tap the peg twice (and vice versa). Three-year-olds did not even pass a pre-test to show understanding of the rules; of children 3.5 years and above, more girls than boys passed the pretest. In the actual test, children started out complying, but younger children could not sustain their attention over time (becoming both faster in responding and less accurate). Although 3-year-olds in another study were to be rewarded for pointing to a box they knew was empty (rather than a box they knew contained candy), they could not inhibit pointing to the baited box (Russell et al., 1991).

According to longitudinal research, impulse control (complying with an adult's rule) is especially challenging for toddlers (particularly for boys), with inhibitory ability developing across the preschool years (Kochanska et al., 1996). Therefore, when using an e-book or touchscreen app, the need to disengage from an interactive element and re-focus attention on the story or educational content might challenge young children's limited ability to regulate their attention and actions (Fisch, 2000; Mayer and Moreno, 2003; Sweller, 2005; Bus et al., 2015). Research on children's developing inhibitory control suggests that interactivity must be used strategically, especially with very young children, to promote learning rather than distraction.

For our app, we chose word learning as an age-appropriate task that would require children's attention. Increasing children's vocabulary is a focus of numerous commercially available apps, and research indicates that preschoolers can "fast map" the association between an object displayed on a screen and its label. For instance, 2-year-olds in one study saw the image of a known object (e.g., a ball) and a novel object on side-by-side computer screens, and a voiceover ambiguously asked them to point to the "glark" (Spiegel and Halberda, 2011). Only by process of elimination (following the "mutual exclusivity" principle) could they figure out the word's referent. After six trials on which they were asked to figure out and point to different named novel objects, they saw all six novel objects simultaneously and were able to pick out whichever one the researchers named. In another study, 2- and 3-year-olds saw an image of an unknown target object in the middle of computer screen while a narrator offered a novel label several times. Then the target disappeared and four images (the target and three unfamiliar foils) appeared together on the screen (Scofield et al., 2007). Children selected the named object at rates above chance, and above the rate at which they selected a non-labeled target (used as a familiarity control). In numerous studies using the preferential looking paradigm, preschoolers have also shown that they can learn the association between an object on a screen labeled in a voiceover and its name (Golinkoff et al., 1987; Schafer and Plunkett, 1998; Werker et al., 1998). Identifying a named object on the screen is the kind of response that would be considered "word learning" in terms of an app, although language researchers distinguish between evidence for initial learning of a word-object mapping and long-term retention of word meaning (Werker et al., 1998; Horst and Samuelson, 2008; Axelsson and Horst, 2013; Bion et al., 2013).

If interactivity is successful and children do learn from a touchscreen, an equally important issue is whether they can apply, or *transfer,* what they learn to the world outside the screen (Barr, 2010, 2013). In an early study using a touchscreen, 15-month-old toddlers failed to transfer a behavior they reliably learned on the screen (pushing a virtual button on a firetruck to elicit a siren sound) to a real toy, or from the toy to the screen (Zack et al., 2009). Older children have been more successful at transfer; for instance, in a study with 27- to 35-month-old preschoolers, researchers pointed out the similarities between the same scene on a touchscreen and on a felt board (a bear and four distinctive 2D hiding places). Then children either were told to touch the bear on the touchscreen so that it would hide, or to watch the bear hide automatically. When children were asked to find the bear on the felt board (that is, to transfer information from the virtual scene), they were more successful in the interactive than the watching condition (Choi et al., 2016). In another study, 30- and 36-month-olds saw videos on a computer screen of puppets hiding in another room, and then were asked to go to the room and find the puppets. Those who pressed a button on the computer to play each "hiding" video more often found the puppet, compared to children who watched the hiding on a non-interactive video, again showing the value of simple, on-task contingency (Lauricella et al., 2010). Furthermore, after 4- to 6-year-old children rearranged a set of virtual rings on pegs on a touchscreen to solve a Tower of Hanoi strategy problem, they solved an analogous 3D problem with real pegs and rings, demonstrating real-world transfer (Huber et al., 2015).

In the research reported here, we examined how children of preschool age physically interact with touchscreen media, and how different types of contingent screen interactions impact children's learning of novel object labels. In Study 1, we designed an app that purposely included "unsupportive, incidental, inconsiderate hotspots" (Zucker et al., 2009) in a tap-the-butterfly filler task that was irrelevant to the main word-learning task. In this preliminary research, we observed how girls and boys physically engaged with the app, focusing on children's tendency to tap on the screen and their ability to inhibit tapping to listen to the narration. Because controlling attention and behavior is especially challenging early in development (Kochanska et al., 1996; Garon et al., 2008), we included Carlson's (2005) snack delay task, an age-appropriate toddler measure of self-regulation, when testing our youngest age group (2-year-olds). We also recruited older preschoolers to use the app, and compared their tapping and word learning to that of the 2-year-olds. In Study 2, we incorporated "supportive, considerate" (Zucker et al., 2009) interactivity – designed to support learning – into a new app and purposely excluded from the design any "inconsiderate" hotspots. We asked children to actively engage with (virtual) novel objects on the screen in a way that might direct attention to them during a naming task. We looked at the connection between different levels of interaction (i.e., *dragging*, *touching*, or *watching* an object move on screen), children's learning of the virtual object's name, and their transfer of the name to the real, depicted 3D object. The results of the two studies provide initial information about how the affordances and design of touchscreen apps may interact with child characteristics to promote or hinder learning.

STUDY 1

Method

Participants

Seventy-seven typically developing, monolingual English-speaking children from a southeastern city in the U.S. participated in this preliminary study using a lab-made touchscreen app. Thirty 2-year-old children (17 males) ranged in age from 23.3 to 35.9 months ($M = 29.4$ months; $SD = 3.5$ months). Additionally, 47 older children (22 males) who came to the lab for other studies played the app (ages 46.1–72.6 months), including a group of 4-year-olds ($N = 22$; $M = 53.9$, $SD = 3.3$), and a group of 5-year-olds ($N = 25$; $M = 66.6$, $SD = 3.8$). Participants were recruited through state birth records and their parents were contacted by telephone. The majority were Caucasian and from middle-class homes. The studies reported here were approved by the university's institutional review board, and written parental informed consent/verbal child assent was obtained.

Materials

We created a touchscreen word learning app using a customizable flashcard app program and displayed it on an 9.5 inch × 7.3 inch (24.1 cm × 18.5 cm) iPad tablet screen. Following the convention in many word learning studies, we included four novel object-label learning trials, as children of this age can learn up to four words per day (Axelsson and Horst, 2013).

The objects appearing in the app were painted wooden toys for which children in previous research did not have names, and similar lab-crafted objects (see **Figure 1** for one object pair). Familiar objects for practice trials on the app were small plastic toy animals. A clear plastic cup, a circular black placemat, and goldfish crackers were used for the self-regulation snack task completed by the youngest age group.

App Design

The app began with brief narration instructing children not to tap the screen until the voice stopped. The app was designed so it would not advance until labeling finished, no matter how many times children tapped. We made this design choice for two reasons: it ensured that all children heard the objects labeled

FIGURE 1 | Examples of novel objects for Study 1.

the same number of times, and allowed us to assess how many times children tapped on the screen during object labeling, despite instructions to the contrary. After word learning trials, to maintain engagement, a screen appeared on which children could tap to make butterflies fly off, followed by a rewarding chime sound.

Procedure

Data were collected in a lab room furnished with a couch, chair, and low table. An experimenter interacted with children, and an assistant recorded the data during the session. Sessions also were videotaped for later coding.

The 2-year-old children first completed Carlson's (2005) toddler snack self-regulation task (based on a measure developed by Kochanska et al., 2000). The task consists of five trials, each escalating in length, wherein the child was presented with a goldfish cracker under a clear plastic cup and told to wait until the bell was rung to retrieve the cracker. In Carlson's instructions, the task ends when children fail a trial by retrieving/eating the treat before the bell rings, or ringing the bell themselves. We used a criterion to create a pass/fail format: children who waited until the bell for all five trials were credited with "high" self-regulation. Those who failed one or more trials were categorized as having "low" self-regulation. We were not able to collect self-regulation data for five participants. Children in the older age groups played the word-learning app after taking part in an unrelated lab task for a separate study, and therefore did not complete a self-regulation task.

Children were introduced to the iPad tablet. The child sat on the couch next to the experimenter and the parent sat nearby in a chair. The assistant watched from behind the child's shoulder to record the data. The tablet sat on a stand on the table in front of the child. The experimenter helped children practice how to touch the iPad screen, making sure they could tap using the pad of their finger so that the device would register the interaction. During this practice, a square on the tablet screen changed color when children successfully tapped.

Next, the experimenter told participants that they were going to play a game, and opened the lab-created word-learning app that taught four novel object labels and took approximately 8 min to complete, depending on how quickly children tapped to advance between screens. Parents were asked to stay silent to enable us to see how children would respond to the app on their own. The experimenter tapped the screen to start the app, which initiated voiceover verbal instructions by a narrator. To familiarize children with the word learning game, the first of a pair of familiar toy animals (cow and elephant) appeared in the center of the screen, one at a time, and each animal was labeled five times by the narrator. After each had been labeled, children had to tap the screen to advance the app; if they did not do so spontaneously, the experimenter encouraged them to "keep playing." On the next screen, the two animals appeared together in different locations than on the labeling slides and the narrator asked the child to touch a specific named animal. Because familiar objects trials served to teach children how to play the game, the children's responses were not analyzed.

After another familiarization trials with a different set of animals (horse and sheep), children advanced to the actual test trials. A target (named) toy or distractor (un-named) toy appeared in the center of the screen (the other toy appeared on the next screen) and the narrator commented on it five times in a voiceover. Narration for the target object included a novel label (dax, fep, blik, or zav) and various carrier phrases spoken in child-directed speech: "Here's the fep! Look at the fep! See the fep? Isn't the fep neat? This is a fep!" Narration for the distractor object included the expression "this one" instead of a label, but was otherwise identical. Then the target and distractor objects appeared together on the test screen and children were asked to "Touch the fep." Object pairings (such as in **Figure 1**) were kept consistent, but the order in which the pairs appeared, and which item of a pair was the target, were counterbalanced across participants. Whether the target or distractor object appeared first, and the location of the target item on the test screen, were counterbalanced across trials. Together, object labeling and children's response on the test screen (for two practice and four actual trials) lasted approximately half a minute per trial.

Between word learning trials, children were presented with a series of three cocoons on the screen. Each time the child tapped a cocoon, a butterfly would appear and fly away with the narration "1", then "2", then "3", followed by a rewarding chime noise. This interactive filler task was included to help maintain engagement and make the lab-created app more similar to a commercial app. Children took approximately 1 m to complete each filler task. Halfway through the word learning trials, we gave children a short break, during which they played with toys for about a minute before completing the final two word learning app trials.

Scoring

Tapping during the introduction and while the novel objects were being labeled was considered "taps during instruction." Taps on the butterflies were considered "filler taps." Trained researchers counted all taps from video of the session, and 26 videos were double coded, with excellent inter-rater reliability (Krippendorf's alpha 0.982, with a 95% confidence interval of 0.972 to 0.991). Children's choice of object (either their tap on or point at an object) on the word learning trials was coded during the session by the assistant and from videotape by a second coder. The few discrepancies between coders (notation mistakes made during sessions) were settled by a third coder, resulting in 100% agreement for all participants.

Results and Discussion

Two-year-old Children

Across the 30 younger children, the mean number of taps during instructions and labeling was 19.2 ($SD = 17.0$), ranging from 0 to 63 taps. According to our criterion for passing the snack delay task, half of the participants were classified as having low self-regulation. We first examined relations between children's tapping on the tablet screen during the app and their self-regulation classification. There were no differences in tapping during the butterflies filler task based on children's self-regulation classification. In contrast, group differences emerged in the number of taps during the "instruction" portions of the app (the initial instructions and the labeling events) when children were instructed not to tap: the 13 children classified as having low self-regulation tapped significantly more ($M = 27.5$ taps, $SD = 20.0$) than the 12 children with high self-regulation [$M = 12.1$, $SD = 12.3$; $t(20.2) = 2.34$, $p = 0.029$, $d = 0.96$] (degrees of freedom adjusted from 23 to 20.2 due to unequal group variances – Levene's test, $F = 5.58$, $p = 0.027$). On average, children who scored lower in self-regulation tapped more than twice as often as their peers during the instructions and labeling. Importantly, these were the parts of the app when children needed to focus attention on the narrator's words. For children with high self-regulation, being able to inhibit tapping allowed them to concentrate on the instruction. The fact that children tapped equally often during the "butterflies" filler portions regardless of self-regulation classification suggests that those with higher self-regulation were equally interested in tapping, but used inhibitory control when the narrator was providing instruction.

A similar pattern was found comparing the tapping behavior of males and females. Boys tapped significantly more during the instruction portions of the app ($M = 26.5$ taps, $SD = 17.3$) than girls did [$M = 9.77$, $SD = 11.2$; $t(28) = 3.02$, $p = 0.005$, $d = 0.96$], but girls tapped as frequently as boys during the filler game. This pattern of results is consistent with reliable sex difference in self-regulation reported in the research literature – specifically, that young males have lower self-regulation than females do (Diamond and Taylor, 1996; Kochanska et al., 1996; Silverman, 2003; Matthews et al., 2009).

Two-year-olds learned 2.33 words on average ($SD = 0.84$ word), ranging from 0 to 4 words. This is a relatively low response rate, given prior evidence that children of this age and younger can reliably learn to associate numerous novel labels with objects depicted on computer and video screens (e.g., Golinkoff et al., 1987; Schafer and Plunkett, 1998; Werker et al., 1998; Scofield et al., 2007; Spiegel and Halberda, 2011). A negative (albeit non-significant) tendency was observed for children who tapped more during instruction to make fewer correct responses on the word-learning task. However, there was also substantial variability in the amount of tapping during instructions, and some 2-year-olds who regulated their tapping still had trouble learning the words. Therefore, this preliminary result suggests an important area for future research: identifying other factors that along with self-regulation might contribute to early learning from touchscreens.

The presence of "unsupportive, incidental, inconsiderate hotspots" (Zucker et al., 2009) in the form of the engaging butterflies filler task between word-learning trials may help explain why toddlers were not more successful in identifying the named objects, since the physical response needed to select the target (tapping) was the same response that was encouraged by the filler task. App designers and parents might be alert for and consider how unregulated tapping behavior (possibly engendered by the app itself) could distract from learning goals, especially for young boys.

Four- and Five-year-old-children

The older children were significantly more successful at inhibiting tapping during the app instructions and labeling (4-year-olds: $M = 6.14$ taps, $SD = 11.6$; 5-year-olds: $M = 2.76$ taps, $SD = 4.16$) compared to the 2-year-olds [$M = 19.2$ taps, $SD = 17.0$; $F(2,74) = 13.3$, $p < 0.001$]. Thus, our results are in line with reports from cross-sectional and longitudinal research that self-regulation (controlling one's actions when required by the situation) increases across the preschool period (Gerstadt et al., 1994; Diamond and Taylor, 1996; Kochanska et al., 1996; Carlson, 2005; Garon et al., 2008). Children of all ages were motivated to tap (shown by statistically equivalent tapping during the butterfly filler task (e.g., 2-year-olds: $M = 7.77$ taps, $SD = 7.70$, 5-year-olds: $M = 4.40$ taps, $SD = 5.89$) but older children could better inhibit their tapping during instruction. These results highlight the particular struggle that very young children have in inhibiting their tendency to tap during moments when they are instructed to wait and listen, such as during teaching moments.

As expected, the older age groups responded correctly on significantly more of the four novel word learning trials (4-year olds: $M = 3.00$ words, $SD = 3.83$; 5-year-olds: $M = 3.36$ words, $SD = 0.76$) than the youngest group did [$M = 2.33$ words, $SD = 0.84$; $F(2,74) = 11.0$, $p < 0.001$]. A trial-by-trial analysis revealed that all age groups responded successfully on the first novel word trial, and the 5-year olds responded correctly on all trials. In contrast, the 2- and 4-year-olds' responses dropped to chance level on the second trial. In some other recent word learning studies, children have shown more robust learning on earlier trials, a kind of "primacy effect" (Horst and Samuelson, 2008; Horst et al., 2010; Zosh et al., 2013). One possibility is that the 2- and 4-year-old children, having succeeded on Trial 1 and then tapped eagerly in the butterfly filler task that followed, did not analyze word learning Trial 2 sufficiently to notice what had now changed (the new object identities and label) that might require a new solution rather than a reflexive response (Aguiar and Baillargeon, 2003). Having experienced two trials, however, some children might extrapolate that certain elements changed across trials, and therefore required focused attention. In fact, the 4-year-olds reliably identified the named target object on the last two trials. The play break with toys that followed Trial 2 may have allowed the 4-year-olds to return and engage with Trials 3 and 4 of the word learning app task less reflexively and more analytically – in Aguiar and Baillargeon's terms, to realize that "a significant change has been introduced that renders [retrieval of a previous solution] inappropriate" (p. 278). In contrast, the 2-year-olds' word learning remained at chance. Given the challenge that some 2-year-olds had in self-regulation and inhibiting their tapping behavior, it may not be surprising that this age group had difficulty focusing on how to use their taps to respond thoughtfully on the later trials, when prepotent (i.e., dominant) responses had been set in motion (Garon et al., 2008). Similarly, young preschool-aged children in prior research had particular difficulty on later trials of executive function tasks requiring focused attention and inhibitory control (Diamond and Taylor, 1996; Gerardi-Caulton, 2000).

A challenge for app design pointed out by Study 1 is the use of a prepotent response (tapping) to assess learning in very young children. Additionally, a more stringent test of word learning is needed than choosing and tapping a novel object on the screen once. Language researchers point out that at minimum, some kind of transfer or generalization task is needed to more clearly show word learning (Werker et al., 1998). Several research teams have provided evidence that "fast mapping" between labels and objects may be only the beginning of really understanding how words refer to entities in the world (Axelsson and Horst, 2013; Bion et al., 2013).

In Study 2, we further examined the effect of both child characteristics and app design on children's learning. Previous research has highlighted the particular benefit of haptic, touch-based exploration (Bara et al., 2007) and particular technology enhancements in e-books (Takacs et al., 2015) for low-SES children's learning. According to recent surveys, SES status is no longer an impediment to touchscreen experience (Smith, 2013; Kabali et al., 2015). Also, we wanted to follow up on the sex differences that emerged in self-regulation between boys and girls in Study 1. Therefore, in Study 2, we probed whether particular kinds of interaction benefitted lower- and/or higher-SES boys' and/or girls' learning.

Regarding app design, we compared the effect of tapping a named object on the screen to a less common, possibly more challenging and engaging behavior: *dragging* an on-screen object. There were at least two possible outcomes of this comparison. On the first account, screen tapping is such a well-practiced, intuitive behavior for most young children that it requires few cognitive resources to carry out. Tapping on relevant/informative areas of the screen promoted learning for at least some preschoolers in recent touchscreen studies (Choi and Kirkorian, 2016; Kirkorian et al., 2016), so tapping may be effective for children of a particular age, sex, and/or SES. An alternative possibility is that the less common, more distinctive, and more motorically challenging behavior of dragging would require children to focus attention to successfully drag the named object, and possibly help them learn its name, similar to the way that distinctive or attention-focusing interactions with a screen promoted adults' learning in previous research (Sapkota et al., 2013; Schwartz and Plass, 2014). In a new app designed for this study, dragging was a functional behavior that fit the requirements of the cover story (to get objects "across a river"), which might make the event (and object) more memorable. However, if dragging the object turned out to be too challenging or cognitively demanding for our participants, this requirement might impede learning. Based on previous research, we expected interacting with the screen to promote learning better than passively watching events (e.g., Strouse and Ganea, 2016). However, it was also possible that engaging in the prepotent tapping response would be less effective than watching for at least some preschool children. Therefore, in Study 2 we compared the two different active manipulation behaviors to merely watching on-screen events, and looked at the relation between these kinds of interactions and preschool children's learning and transfer of novel object labels.

STUDY 2

Method

Participants

The participants were 182 children from 2 to 4 years of age and their parents. Twelve children were unwilling to complete the task and their data were dropped from analyses, leaving a total of 170 children (M = 41.05 months, SD = 10.51; 82 males) divided into three age groups (see **Table 1**). Some were recruited through state birth records (N = 52) and others through local daycare centers and preschools (N = 118). Participants were randomly assigned to one of three conditions, with the caveat that sex and mean age were equated across condition as much as possible: *Watch* condition (N = 58, M = 40.6 months, SD = 10.6 months); *Tap* condition (N = 60, M = 40.8 months, SD = 10.5 months); *Drag* condition (N = 52, M = 41.8 months, SD = 10.5 months). The children were from families with various ethnic backgrounds: parents identified their child as White (62%), Black or African–American (25%), Asian (3%), Biracial or mixed race (5%), or chose not to disclose their child's race (5%). Socioeconomic status (SES; parents' highest completed education levels) ranged from high school diploma or less (7.1%) to at least some graduate or professional training (44.1%).

Materials

A new word-learning app, programmed for us by an undergraduate engineering student, was displayed on a 10.1″ Samsung Galaxy Tab 2 with a 21.7 cm × 13.6 cm active screen area (see **Figure 2**). The app was programmed to automatically record the location, frequency, and time of the participant's taps or drags on the screen. In the new app, the same familiar and novel objects were labeled as in Study 1. Real, 3D versions of the objects shown on the tablet were also used along with a plastic bucket to contain them. Parents completed a short survey about family demographics and their child's media use.

Procedure

Children played the word-learning app at the lab after participating in a separate, unrelated study not involving a tablet, or in a quiet room of their daycare center or preschool. Depending on condition, they either watched (*watch* condition) or played (*tap* and *drag* conditions) the word learning game

TABLE 1 | Mean (standard deviation) age (in months) for the three age groups by gender in Study 2.

	Male	Female
	n = 28	n = 21
2-year-olds	27.2	28.0
	(3.56)	(3.70)
	n = 45	n = 39
3-year-olds	42.3 (3.67)	43.1 (2.82)
	n = 15	n = 22
4-year-olds	55.4	55.3
	(3.35)	(3.59)

A
B


FIGURE 2 | One pair of novel objects for Study 2: (A) during labeling; and **(B)** after labeling, during a dragging interaction.

on a touchscreen tablet held for them by the experimenter. An assistant unobtrusively coded the interaction while watching over the child's shoulder. As in Study 1, the first two pairs of objects were familiar animals. These trials served to familiarize the child with the game, but children's responses were not analyzed. The last four (test) trials involved the novel objects and object labels used in Study 1.

Game Play

The app opened with an introductory screen narrated in a voiceover: "Let's play a game!" The introduction of familiar and novel objects was the same for participants in all conditions. To begin a trial, the app introduced each of a pair of objects, which appeared on a white background one at a time. During the familiarization trials, each animal appeared in turn and was labeled three times. During the test trials, the novel target object was labeled and the distractor object was called "this one." For example, the target object appeared on the screen, accompanied by the narration, "Look at the Dax! See the Dax? Isn't the Dax neat?" Then the target object disappeared and the distractor object appeared with the narration, "Look at this one! See this one? Isn't this one neat?" Again, the object pairings were kept consistent, but the order in which the pairs appeared and which novel object of the pair served as the target were counterbalanced across participants. Whether the target or distractor object appeared first was counterbalanced across the trials.

After a pair of familiar or novel objects was introduced, the app entered the interactive portion. Against a cartoon backdrop of a field bisected by a river (**Figure 2**), one of the pair of objects appeared on the left and the app narrator told the child, "[The ____ /This one] needs to get to the other side of the river." Then, depending on condition (and using carrier phrases of equal length in each condition), the app instructed the child either to: (1) "*Watch* [the ____ /this one] move across the river!"; (2) "*Tap* [the ____ /this one] and it will move!"; or, (3) "*Drag* [the ____ /this one] and it will move!" Following this instruction and the child's response, when each object reached the far side of the river it was labeled one final time: "Yay! [The ____ /This one!]" followed by a rewarding chime sound.

The next screen offered a test of the child's word learning. The pair of objects appeared against a white background, in different locations than during labeling. The narrator asked about the labeled object, "Where is [the ____]?" Regardless of the child's choice (touch response), the app continued with the two objects appearing in new locations on the screen, and the app narrator asking, "Where is [the ____] now?" The child did not receive feedback from the app or experimenter on their selections. Each of the six trials (two with familiar objects and four with novel objects) lasted approximately 1 min and there was no off-topic "filler" task.

After each trial with the tablet, the child was tested using the corresponding 3D objects. The experimenter dumped the pair of objects out of the bucket in front of the child, extended her hand on the midline of her body toward the child and asked the child to place the target object in her hand (e.g., "Can you put the Dax in my hand?"). No feedback was given to the child. This sequence took approximately 20 s and was repeated for each of the six pairings (two familiarization/familiar object trials and four novel object trials).

Scoring

The assistant recorded children's object selections (depicted on the tablet and with the real objects) during the session. Children's touches of an object in the app also were retrieved from the output log on the tablet. A second coder scored children's real object selections from videotape of the sessions, resulting in 100% agreement across the two coders. To be considered correct on learning an object label on the tablet, children needed to select the named target object in response to both requests to identify it in the app. These strict criteria aimed to avoid giving children credit for word learning that was merely chance selection. Because transfer from the app (the virtual target object) to the real world (the real target object) depended on learning the information in the app, to receive credit for the real object transfer, children needed to select the target object both times in the app, and then select the real, 3D target object.

Socioeconomic status was measured as the average of the two parents' (or the sole parent's) education levels (as reported by parents on the survey); education level tends to reflect SES more accurately than income does in our population. In our relatively educated sample, the data were grouped into three categories, each containing about a third of participants: *low SES* parent education corresponded to some high school through some college education; *middle SES* corresponded to a bachelor's degree through some graduate work; and *high SES* corresponded to a master's or doctoral degree. Parents reported children's exposure to touchscreens as the amount of time (in hours) that their child *actively interacted with a touchscreen* in a typical day, excluding such non-interactive uses as watching movies on a touchscreen device.

Results and Discussion

Children in all age groups learned some words from the tablet, and sometimes transferred what they learned to the real object (see **Table 2**). We first examined parents' responses to the survey items and the relation between SES and touchscreen exposure. In the analyses below, the degrees of freedom reflect the inclusion of covariates and some missing data in survey items, such as SES reporting.

Descriptive Statistics: SES

Parents reported their highest attained education level as either a high school diploma or less (7.7% of families), some college work/Associate's degree (20.6%), Bachelor's degree (28.2%), some graduate work (4.1%), Master's degree (22.4%), or Doctoral degree (11.2%); 5.8% declined to disclose their education level. Dividing families into three relatively equal SES groups resulted in 58 children in the *low SES* group, 54 children in the *middle SES* group, and 47 children in the *high SES* group.

Touchscreen Exposure

Children across our whole socioeconomic range had prior exposure to touchscreens, but there were intriguing SES differences. Even after controlling for age, there was a significant difference in the amount of time children spent with touchscreens depending on their parents' education level, $F(2,148) = 8.38$, $p < 0.001$, $\eta^2 = 0.102$. Pairwise comparisons (with age-covaried Bonferroni corrections) revealed that children from lower SES families spent significantly more time with touchscreens per day ($M = 1.50$ h, $SE = 0.16$) than children from both middle SES families ($M = 0.77$ h, $SE = 0.16$; 95% CI [0.18, 1.27], $p = 0.005$) and high SES families ($M = 0.61$ h, $SE = 0.17$; 95% CI [0.32, 1.45], $p = 0.001$). Thus, children from lower SES families spent approximately 90 min per day on touchscreens compared to 35–45 min per day for children from middle-and upper-SES families. In contrast, there was no significant difference in the amount of time children of different SES backgrounds watched television—a result that differed from what has previously been reported (Anand and Krosnick, 2005; Fairclough et al., 2009). Because prior exposure to touchscreens differed across SES, we controlled for these factors in subsequent analyses of word learning.

TABLE 2 | Mean number of words (out of four) learned on the tablet and transferred to the real object for the three age groups in Study 2; standard deviations in parentheses.

	Tablet	3D Transfer
2-year-olds	2.22	1.49
	(1.25)	(1.17)
3-year-olds	3.04	2.68
	(1.06)	(1.28)
4-year-olds	3.03	2.95
	(0.96)	(1.03)

Analysis by Age

Children's word learning was similar to that found in Study 1 (see **Table 2**). In an initial Analysis of Covariance (ANCOVA), a significant age difference emerged in words learned from the touchscreen app (as measured by children's responses on the tablet). The age difference remained after controlling for SES and prior touchscreen exposure, $F(2,145) = 11.0$, $p < 0.001$, $\eta^2 = 0.132$. Pairwise comparisons (with a Bonferroni adjustment) indicated that 2-year-old children learned significantly fewer words than 3-year-old children (mean difference of −0.91 word, 95% CI [−1.41, −0.42], $p < 0.001$) and 4-year-old children (mean difference of −0.84 word, 95% CI [−1.43, 0.25], $p = 0.002$). Word learning by the 3- and 4-year-old children in our assessment on the tablet was equivalent.

For each age group, we used a paired sample t-test to compare children's word learning on the tablet to their transfer of the label to the actual object. Recall that to receive credit for transferring a word, children needed to have first learned the word on the tablet. Statistically equivalent scores on the tablet and transfer word learning scores would indicate successful transfer of learned words. The results suggest that only the 4-year-old children were proficient in transferring their learning from the tablet to the real 3D objects, with no significant difference between their scores on the two tests of word learning, $t(36) = 1.78$, $p = 0.083$, see **Table 2**. In contrast, there were significant differences in word learning scores on the tablet compared to transferring the labels to the real objects for the 2-year-olds, $t(48) = 5.98$, $p < 0.001$, and 3-year-olds, $t(83) = 4.34$, $p < 0.001$. Because of the clear age difference in word learning, we controlled for age in the remaining analyses.

Analysis by Socioeconomic Status (SES)

A two-way ANCOVA revealed a significant interaction between condition (watch, tap, drag) and SES (parental education: low, medium, high), on children's word learning, controlling for age, $F(4,149) = 2.46$, $p = 0.048$, $\eta^2 = 0.062$ (see **Figure 3**). Pairwise comparisons revealed that word learning of low-SES participants, as tested in the app, differed in the interactive tapping and dragging conditions: with a Bonferroni adjustment for multiple comparisons (and controlling for age), participants from low-SES families learned more words by *dragging* the named object ($M = 3.09$, $SE = 0.26$) than by *tapping* it ($M = 2.22$, $SE = 0.20$), with a mean difference of 0.87 word, 95% CI [0.81, 1.66], $p = 0.025$. In the transfer test with the 3D objects, this pattern remained but was non-significant.

Analysis by Sex

We also looked for any sex differences in children's word learning (as assessed on the tablet) using a two-way ANCOVA controlling for age and SES. There were no main effects of sex or condition, but a significant sex × condition interaction

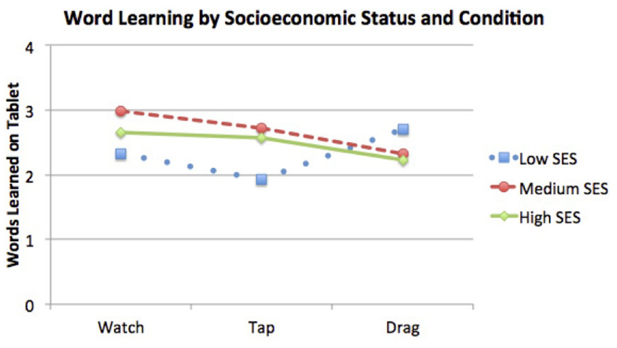

FIGURE 3 | Number of words learned by children in Study 2 (all ages included) from the three SES groups in the three app interaction conditions, with age covaried. Children from low SES families (dotted line) learned significantly more words after dragging, compared to tapping, the named object on the screen.

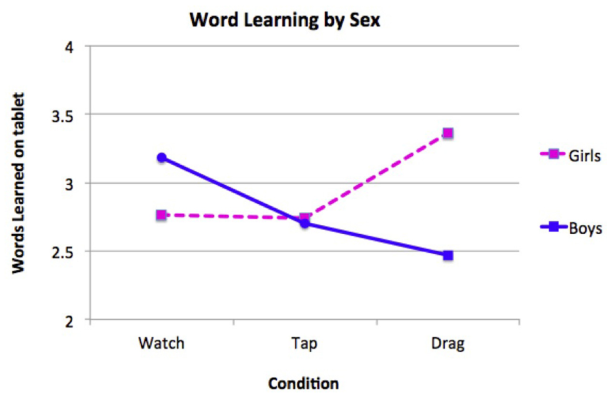

FIGURE 4 | Word learning (assessed on the tablet) by boys and girls of all ages and SES groups in Study 2. With SES and age covaried, girls outperformed boys in the interactive *drag* condition, and boys learned significantly more in the non-interactive *watch* condition than in the interactive *drag* condition.

emerged, $F(2,151) = 5.09$, $p = 0.007$, $\eta^2 = 0.063$ (see **Figure 4**). According to a pairwise comparison (with Bonferroni adjustment for multiple comparisons, controlling for age and SES), girls who dragged named objects learned significantly more of the four words ($M = 3.36$, $SE = 0.23$) than boys did ($M = 2.47$, $SE = 0.20$) – a mean difference of 0.89 word, 95% CI [0.30, 1.49], $p = 0.004$. Another pairwise comparison (with the same adjustments and covariates) indicated that boys in the non-interactive watch condition learned significantly more words ($M = 3.18$, $SE = 0.20$) than boys in the interactive drag condition ($M = 2.47$, $SE = 0.20$), with a mean difference of 0.71 word, 95% CI [0.04, 1.39], $p = 0.034$. Identical (though non-significant) trends for all condition × sex differences emerged when analyzing real object word-learning transfer.

We further investigated girls' and boys' word learning on the tablet using follow-up ANCOVAs split by age group, controlling for variance contributed by SES. A significant interaction between sex and condition emerged only for the 3-year-olds, $F(2,73) = 5.19$, $p = 0.008$, $\eta^2 = 0.125$. Pairwise comparisons (with a Bonferroni adjustment and SES covaried) reveal that in the drag condition, 3-year-old girls learned significantly more words ($M = 3.98$, $SE = 0.38$) than 3-year-old boys did ($M = 2.58$, $SE = 0.25$), with a mean difference of 1.40 words, 95% CI [0.49, 2.32], $p = 0.003$. A similar, marginally significant result favoring girls in the drag condition emerged in the 4-year-olds, with a mean difference of 0.97 words, 95% CI [0.002, 1.94], $p = 0.050$). Further, 3-year-old girls learned more words when they dragged the named objects ($M = 3.98$, $SE = 0.38$) than when they simply watched the objects move without interacting with the screen ($M = 2.78$, $SE = 0.30$), although this 1.20-word difference was only marginally significant, 95% CI [−0.003, 2.41], $p = 0.051$. A possible explanation for girls specifically benefiting from the motorically challenging drag condition involves preschool sex differences in fine motor development favoring girls (Moser and Reikerås, 2016).

Analysis of Tapping Frequency

A one-way Analysis of Variance (ANOVA) showed a significant condition difference in the amount that children tapped during instruction (when the app narrator was speaking), $F(2,166) = 14.9$, $p < 0.001$. Tukey *post hoc* comparisons revealed that children in the watch condition tapped significantly less than those in the tap condition, with a mean decrease of 28.3 taps, 95% CI [−43.7, −13.0], $p < 0.001$. Children in the watch condition also tapped significantly less than those in the drag condition, with a mean decrease of 33.6 taps, 95% CI [−49.5, −17.7], $p < 0.001$. Specifically, children who *watched* the objects move across the screen tapped on average 10 times during the instruction throughout gameplay, whereas children who *interacted* with the app through tapping or dragging tapped an average of 38 and 44 times, respectively, when they were supposed to be listening. This tapping difference points to one potential mechanism to explain why the children (particularly boys) in the non-interactive watch condition performed better overall than those in the interactive tap condition. That is, tapping during the interaction portions may have primed or elicited additional taps during times that children were instructed *not* to tap, and thus distracted them from encoding the novel object labels. Why, then, did participating in the drag condition (which apparently elicited even more extra taps) still promote learning, at least for girls? Some provisional hypotheses are presented below.

GENERAL DISCUSSION

In the studies reported here, we offer some exploratory insight into how young boys and girls of different ages and family backgrounds interact with touchscreens, and how various types of touch interactions impact learning. Our focus was preschool children's physical interactions with a touchscreen app, their self-regulation, and their word learning from the screen. We expected that toddlers' ability to inhibit a dominant response to tap on the screen might be related to their self-regulation as assessed by Carlson's (2005) snack task, an age-specific standard measure of this aspect of executive function. In Study 1, we purposely designed our simple word-learning app to promote children's interaction with the screen. To make the app more similar to commercial products that young children use, between the four word-learning trials we inserted a filler task of tapping on butterflies to produce a rewarding chime sound. This off-topic task kept children engaged, but it also may have primed children's tapping response. We found that 2-year-olds who scored lower on self-regulation tapped more than twice as often while the narrator was labeling objects compared to toddlers with higher self-regulation. Children with better inhibitory control tapped just as frequently as other children during the butterflies screens, but inhibited their tapping during the instruction portions of the app. Compared to the toddlers, older children (4- and 5-year-olds) were significantly better at controlling the tapping response during the app's instructions and object labeling. This pattern of results fits with cross-sectional and longitudinal evidence that the ability to control one's actions when required by the situation increases across the preschool period (Diamond and Taylor, 1996; Kochanska et al., 1996; Gerardi-Caulton, 2000; Carlson, 2005; Garon et al., 2008). Our results should alert parents and media professionals to the particular challenge infants and toddlers will face listening to instructions explaining how to play and narration aimed at teaching, when a learning device responds to their touch.

Children of all ages learned the new word on the first trial in Study 1, showing that even 2-year-olds can learn a novel object label from a touchscreen. However, only the older children were reliable word learners over trials. The younger children in both studies had a tendency to tap more over time: they tapped more on the fourth trial than the first trial, although the difference did not reach statistical significance. This tendency echoes the results of studies of inhibitory control in which young children started out following directions, yet ended up responding quickly but inaccurately by the later trials (e.g., Gerstadt et al., 1994; Diamond and Taylor, 1996; Gerardi-Caulton, 2000). In Study 2, 2- and 3-year-olds learned words as assessed within the app, but the oldest children alone (4-year-olds) were proficient at transferring the new object labels to the actual, 3D objects when tested immediately afterward.

Word-learning tasks in which a recorded voiceover labels a close-up of a single object on a laptop (Scofield et al., 2007) or one of a pair of objects on a video or computer screen (e.g., the "preferential looking paradigm"—Golinkoff et al., 1987; Spiegel and Halberda, 2011) are relatively common. However, language researchers point out that making initial word-object associations is not the same as forming an enduring, rich understanding of a word that allows a child to generalize that word's meaning to novel exemplars (Werker et al., 1998; Horst and Samuelson, 2008; Axelsson and Horst, 2013; Bion et al., 2013; Zosh et al., 2013).

The current results are in line with a general "transfer deficit" that has been reported in many previous studies with screen media including touchscreens (e.g., Barr, 2010, 2013). An important take-away message is that even when young children "get the answer right" within an app, adult support may be needed for children to apply educational information to the world outside the screen (Barr, 2010, 2013; Troseth et al., 2016). When possible, research investigating children's learning from touchscreen apps should include 3D transfer tasks to measure children's generalization of learning.

In Study 2, we compared the effect of children's *tapping* on labeled objects to get them to move "across the river," *dragging* those objects to move them, or merely *watching* the object move on the screen. There were no overall main effects for which behaviors led to the best word learning. However, there were intriguing interactions involving the learning of children from lower- versus higher-SES families, and of girls compared to boys.

Participants from lower-SES families (where parent reported attaining "some high school" to "some college") learned more (3 of 4 words) by dragging named objects than by tapping objects to get them to move (just over 2 words). Parent survey data hints at a potential explanation. Children from our lower SES families spent, on average, 90 min per day with touchscreens—at least twice as long as children from the middle- and high-SES groups did. Given our lower-SES children's relatively abundant touchscreen experience, screen tapping may have been an especially well-practiced, dominant response that was less distinctive than dragging. Typically, lower-SES children's fine motor development is delayed compared to that of more advantaged children (Piek et al., 2008; Miquoelote et al., 2012; Aiman et al., 2016; Comuk-Balci et al., 2016). However, one contributor to fine motor development (often related to SES) is access to and experience with play materials (Miquoelote et al., 2012). Compared to low-SES groups in prior research, the children in our lower-SES group may have differed in important ways (e.g., many attended a high-quality preschool for low-income families) or their ample exposure to touchscreens may have trained up the specific fine motor abilities needed to interact with the screen.

Dragging was likely to be a relatively novel screen behavior, a more challenging fine motor skill than tapping (requiring focus to accomplish). As a relatively distinctive behavior, dragging a named object may have been more memorable, and a mental representation of the event easier to retrieve, compared to tapping an object to get it to move (similar to why iconic movements incited deeper processing in adults—Schwartz and Plass, 2014). Additionally, the act of dragging objects during the labeling phase was different from the response required during the app-based word-learning *test* (i.e., tapping on the target object when asked to choose). In Aguiar and Baillargeon's (2003) account of infant problem solving and perseveration, the authors reason that individuals engage in deep processing of a problem when they realize that they cannot apply their previous response to the new problem. Switching between dragging during labeling and tapping during the test may have assisted children who possessed the requisite fine motor skill to respond more intentionally to each new event than in the tapping condition, when the response during labeling and test was the same.

Across SES groups, dragging was more helpful for girls than for boys, especially for the 3- and 4-year-olds. Looking across conditions, 3-year-old girls learned more after dragging named objects (nearly all had perfect scores) than after passively watching the objects move. Boys, on the other hand, learned more in the non-interactive watch condition than in the interactive drag condition. A partial explanation for this sex difference may be more advanced fine motor development in girls during the preschool years (Comuk-Balci et al., 2016; Moser and Reikerås, 2016). Compared to tapping an object, dragging it also is likely to require greater focused attention, monitoring of success, and repair of failures—behaviors that depend on executive function skills such as inhibitory control and selective attention. Earlier development of such self-regulatory behaviors in girls compared to boys (e.g., Kochanska et al., 1996, 2000; Silverman, 2003; Matthews et al., 2009) may explain why the older preschool girls in our research were able to benefit from the dragging response.

Dragging is merely one example of a behavior that, at least for some preschool-aged children, appears to be challenging enough to promote focused attention, while not being too difficult in terms of motor skills. In research with adults, Schwartz and Plass (2014) had participants drag a virtual object (such as an eraser) on a thematically related background (e.g., a blackboard) as an "iconic" movement related to the meaning of a to-be-learned phrase (e.g., *erase the blackboard*). For adults, enacting a *meaningful* action promoted better memory than if they merely clicked and the object moved on its own. Iconic movement served to recruit conceptual information (about erasers and blackboards) and offered multi-sensory retrieval cues for recalling the target phrase after a delay. Dragging was contextually relevant within the app storyline of the object needing to get across the river. This meaningful context for the action of dragging may have served to focus sustained attention on the named target object, helping children with the requisite fine motor control and ability to focus to remember its label at the test.

We had expected tapping on named objects to promote more learning than watching without interacting, but such was not the case for our participants. In previous research with adults and children, tapping or clicking on a relevant item increased learning compared to merely watching an item move (Sapkota et al., 2013) or tapping elsewhere on the screen to advance the action (Choi and Kirkorian, 2016; Kirkorian et al., 2016). Similarly, children who pressed a button on a computer to get videos to play learned more than children who watched non-interactive video (Lauricella et al., 2010).

An analysis of children's tapping behavior in Study 2 by condition is illuminating. Across the duration of the app, children who *watched* the objects "move across the river" tapped a total of only 10 times, on average, during the narrator's instruction (when objects were being labeled), whereas children who *tapped* on objects to make them move went on to tap on average four times as often during instruction, when they were supposed to be listening. Interacting with the screen by tapping to move the labeled object may have primed children's prepotent tendency to tap reflexively on the screen, which then carried over into periods of instruction, possibly distracting children from focusing on the words. In the context of tapping across all app segments, tapping the target objects may have been more *reflexive* (automatic) than *reflective* (with deep processing of the object's identity). Thus, tapping as an interactive behavior may not have effectively directed children's attention.

Children in the drag condition also tapped four times as often during instruction compared to children in the watch condition. The fact that children who watched without interacting tapped comparatively seldom may help explain why boys in particular (with their less-advanced self-regulation ability compared to girls) learned better when they watched than when they interacted with the screen by dragging: they were more likely to learn from touchscreens in situations that did not prime them to touch the screen (and thus reduced the chances of distraction).

An exception to this pattern was found in low-SES children in the watch condition. There was no overall interaction between SES and condition in the amount that children tapped on the screen. However, with age covaried, a marginal difference in tapping frequency emerged between the low SES group and the other groups, which is specifically apparent in the *watch* condition, in which the lower SES children tapped much more (18.7 taps) compared to the middle SES (6.39 taps) and the high SES groups (7.11 taps). Based on the connection between tapping and self-regulation in Study 1, we might infer that the low-SES children in Study 2 were exhibiting lower self-regulation, a finding commonly reported in the literature (see Sarsour et al., 2011, for a review). However, when app gameplay involved directed interaction (the request to *tap* or *drag* objects), there was no difference in the number of taps elicited between the SES groups.

Dragging the named object did help the girls—despite the extra tapping that was engendered by interacting with the screen. As mentioned earlier, for children with better self-regulation (and fine motor control), dragging recently labeled objects may have been optimally challenging so as to focus attention on the object being moved. Thus, dragging named objects may have resulted in memorable event representations that promoted word learning, despite the fact that interacting with the screen also promoted children's tapping when the narrator was offering the object labels. Similarly, dragging seemed to help the lower-SES children, experienced touchscreen users, to focus on and learn the words, whereas watching events on the touchscreen engendered excessive tapping.

The research reported here has several limitations. Although we measured 2-year-olds' self-regulation in Study 1, we did not collect this data from the other children. Future independent assessment of older girls' and boys' self-regulation and fine motor skills will help to support or refute our suggestions of mechanisms underlying the differential benefits of the various kinds of interactions. Our word-learning apps were not commercial products, so were limited in many ways compared to touchscreen app products developed to teach language. Additionally, as is suggested by parents' responses to our media survey (which differed from published survey results from a few years earlier—e.g., Anand and Krosnick, 2005; Fairclough et al., 2009), "children's experience with media" is a moving target; exposure to new products and technology will continue to change the skills, expectations, and responses that children bring to the experience of learning from educational technology.

The current research involved a learning app that directed children what to do. Thus, it does not answer questions about how children learn during self-directed exploration on a touchscreen. In intentional exploratory learning, a person decides to examine a new object, sight, or sound, instead of being told or guided to do so. Intrinsically motivated actions (*volitional movements)* allow a child to choose how they wish to engage with material, and intrinsic motivation is important in creating engaged learners (Hirsh-Pasek et al., 2015). Previous research has shown that when adults explored a virtual on-screen environment, periods of active, intrinsically motivated exploration (compared to times when the person was not moving) were marked by increased responses in areas of the hippocampus involved in learning and memory. Furthermore, those increased responses predicted learning, memory, and later performance accuracy (Kaplan et al., 2012). Self-directed actions on a touchscreen might similarly promote children's active processing and learning.

The message emerging from research, including the current studies, is that interactivity from touchscreens is a double-edged sword: on the one hand, haptic engagement (including touches on a responsive screen) can direct attention and focus and contribute to learning in adults (Smith and Olkun, 2005; Sapkota et al., 2013) and children (Huber et al., 2015; Choi and Kirkorian, 2016; Kirkorian et al., 2016). On the other hand, research indicates that interactivity in the form of hotspots and games can actually distract from learning (Takacs et al., 2015) due to the need for a child to "task switch" or disengage from the interactive feature and selectively re-focus on educational content (Fisch, 2000; Sweller, 2005; Mayer and Moreno, 2003; Bus et al., 2015). Given young children's limited ability to regulate their own attention and actions, developers of children's media must think strategically about using interactivity in ways that benefit, rather than hinder, learning. In a recent study with toddlers, for instance, Strouse and Ganea (2016) zeroed in on differences between more and less helpful interactivity for this age group: very simple interaction, such as having to tap on an object to turn the page, helped toddlers learn a word, but if the tap elicited an engaging but "off-topic" visual and auditory reward, children's learning suffered.

A hopeful finding in the current research was that lower-SES children (defined as children whose parents had less education) learned better in the challenging condition that required dragging named objects, compared to the condition that called for a tap response. Well-designed interactive technology holds great promise for giving children from less advantaged families additional engagement with educational content, particularly as touchscreen devices have now become prevalent across all income levels (Kabali et al., 2015). Differences in how girls and boys (or children of different ages) learn best can be met by making digital technology customizable (e.g., including a parent control panel) so parents and educators can tailor an app by choosing an interactive style that best fits the child. Developers can utilize play testing to observe how children with different characteristics engage with the app, and try to accommodate as many types of beneficial interaction styles as possible.

Our studies highlight a significant but perhaps overlooked aspect of children using educational technology: that *how* a child interacts with an app may be as important as the app's content in determining how much a child learns. Parents and industry experts should consider a child's age, sex, level of self-regulation, screen experience, and the physical requirements of engagement with touchscreens when designing, choosing, and studying educational apps for children.

ETHICS STATEMENT

This study was carried out in accordance with the recommendations of and approval of the Vanderbilt University Institutional Review Board. All parents of children who participated gave written informed consent, and all participating children gave verbal assent, in accordance with the Declaration of Helsinki. Children were given the option to cease participation at any time if they did not want to continue.

AUTHOR CONTRIBUTIONS

CR-J and GT oversaw both studies. CR-J, GT, and CD contributed original ideas for both studies. CD led data collection for Study 1, AM led data collection for Study 2. CR-J, GT, AM, and CD wrote the manuscript.

FUNDING

The research in this publication was supported by a National Science Foundation Graduate Research Fellowship to Colleen Russo (DGE: 14445197); by Peabody College, Vanderbilt University; and by the EKS NICHD of the NIH under Award #U54HD083211. The content is solely the responsibility of the authors and does not necessarily represent the official views of the NIH.

ACKNOWLEDGMENTS

We thank Nolan Michael Smith for developing the app used in Study 2, and the undergraduate researchers, parents, and children who participated.

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Conflict of Interest Statement: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

frontiers in Psychology

ORIGINAL RESEARCH
published: 21 February 2017
doi: 10.3389/fpsyg.2017.00179

Addressing the Math-Practice Gap in Elementary School: Are Tablets a Feasible Tool for Informal Math Practice?

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Students rarely practice math outside of school requirements, which we refer to as the "math-practice gap". This gap might be the reason why students struggle with math, making it urgent to develop means by which to address it. In the current paper, we propose that math apps offer a viable solution to the math-practice gap: Online apps can provide access to a large number of problems, tied to immediate feedback, and delivered in an engaging way. To substantiate this conversation, we looked at whether tablets are sufficiently engaging to motivate children's informal math practice. Our approach was to partner with education agencies via a *community-based participatory research* design. The three participating education agencies serve elementary-school students from low-SES communities, allowing us to look at tablet use by children who are unlikely to have extensive access to online math enrichment programs. At the same time, the agencies differed in several structural details, including whether our intervention took place during school time, after school, or during the summer. This allowed us to shed light on tablet feasibility under different organizational constraints. Our findings show that tablet-based math practice is engaging for young children, independent of the setting, the student's age, or the math concept that was tackled. At the same time, we found that student engagement was a function of the presence of caring adults to facilitate their online math practice.

Keywords: IXL, technology, math learning, ipad, math education

OPEN ACCESS

Edited by:
Gabrielle Strouse, University of South Dakota, USA

Reviewed by:
Paula Jane Hubber, University of Nottingham, UK
Alexis Lauricella, Northwestern University, USA
Fashina Alade, Northwestern University, USA

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Specialty section:
This article was submitted to Developmental Psychology, a section of the journal Frontiers in Psychology

Received: *11 August 2016*
Accepted: *26 January 2017*
Published: *21 February 2017*

Citation:
Stacy ST, Cartwright M, Arwood Z, Canfield JP and Kloos H (2017) Addressing the Math-Practice Gap in Elementary School: Are Tablets a Feasible Tool for Informal Math Practice? Front. Psychol. 8:179. doi: 10.3389/fpsyg.2017.00179

INTRODUCTION

"Math is hard."
Will, 11

To what extent does math competence depend on informal math practice (IMP)? Surprisingly, there is very little research on this question, which stands in sharp contrast to the amount of research on informal reading practice. We argue that IMP faces practical barriers: Math practice is far more difficult to carry out informally than reading practice, creating a "math-practice gap". Thus, to help students develop math competence, a solution to the math-practice gap needs to be found. In the current paper, we look at the use of online math apps as a possible solution. Specifically, we ask whether tablets are sufficiently motivating for children to engage in math practice outside of school-required assignments and homework.

In what follows, we will first justify the need for IMP to supplement in-class math education, focusing specifically on elementary-school arithmetic. We then discuss the practical barriers to IMP and how tablets could address these challenges. Central to our argument is that math practice needs to be interactive and individualized, providing students with a sustained positive experience of success. This cannot be done easily without online support, which is where research on tablet feasibility comes in. We carried out such a feasibility study, using a community-based participatory research design. While this method does not allow for a precise control of variables, it has the advantage of maximizing ecological validity.

The Nature of Math: How Important is Practice?

The importance of practice is well known: No matter what the skill, practice is likely to benefit competence (e.g., Kanive et al., 2014). At the same time, mindless drill has fallen out of favor, along with memorization and busy-work (cf., Delpit, 2012) Indeed, a search through the literature reveals a focus on didactics (how to convey a math concept) – more so than a focus on math practice. This leaves little empirical guidance to determine what kind of math practice might be best. We will go another route to look at this question: We will first examine the mental activities needed to solve a math problem. We will then contrast them with the mental activities that are needed to read. Reading, as it turns out, is a domain that has enjoyed a long track record of established findings on informal practice (e.g., Rasinski, 1990; Pikulski and Chard, 2005). Thus, a side-by-side comparison between math-related mental activities and reading-related mental activities allows us to make inferences about math practice.

Our focus is specifically on elementary-school arithmetic and the concepts outlined in the Common Core State Standards Initiative (2011). They include operations with integers (i.e., addition, subtraction, multiplication, division), operations with fractions (e.g., ordering of fractions on the number line, equivalent fraction, improper fractions) and operations with decimal numbers (e.g., place values, correspondence between decimals and fractions). Overall, this domain has several advantages for the purposes of the current feasibility study: For example, there is a high variability in concepts (e.g., National Council of Teachers of Mathematics, 2000), making it possible to derive generalizable claims. Elementary school is also the time during which children learn to read, giving credence to a side-by-side comparison. **Table 1** summarizes our reflections on mental activities likely to be required at each grade level. As can be seen from the table, the challenges for the mind are likely to be far greater for math than for reading, independent of what is covered at each grade level. In the remainder of this section, we fully describe these differences.

TABLE 1 | Assumed mental activity for reading and math in K-6 grades.

Grade/Subject	Content	Challenge for the Mind
Kindergarten		
Reading	Letter system	Attention to detail
Math	Number system	Attention to detail, precision, abstractness
1st Grade		
Reading	Reading words	Attention to detail, fluency
Math	Addition/subtraction	Attention to detail, precision, fluency
2nd Grade		
Reading	Reading sentences	Attention to detail, fluency
Math	Multi-digit operations	Attention to detail, precision, fluency, relational reasoning, alternate meanings
3rd Grade		
Reading	Reading paragraphs	Fluency
Math	Multiplication/division	Abstractness, precision, interfering fluency
4th Grade		
Reading	Reading essays	Fluency
Math	Fractions	Abstractness, attention to detail, precision, interfering Fluency, alternate meaning, relational reasoning
5th Grade		
Reading	Reading chapters	Fluency
Math	Decimals	Abstractness, attention to detail, alternate meaning
6th Grade		
Reading	Reading chapter books	Fluency
Math	Negative integers	Interfering fluency, attention to detail, alternate meaning

In Kindergarten, math is primarily about mapping symbols to quantities, which requires attention to detail. This mimics the mental activity that is required for reading. But beyond attention to detail, the mind also needs to apply a precise counting routine. And it needs to detect the abstractness of number (i.e., that a number refers not just to entities, but also to time, distance, or events). None of these mental activities are required for reading, suggesting that the amount of practice needed for math may already be higher than the amount of practice needed for reading.

In 1st grade, math is about addition and subtraction, which is yet another set of routines. By 2nd grade, children need to expand this fluency to multi-digit numbers, which further adds to the set of precise routines. Note that multi-digit numbers provide mental challenges of their own: Consider, for example, the numbers [*20*] and [*02*]. Even though the individual digits are the same in both cases, their meaning is vastly different, even unconventional in the latter case. Thus, the meaning of a digit is defined by its spatial location – a feature that has very little ecological validity for children (i.e., few entities change meaning because of where they are in relation to other entities). Furthermore, there is no statistical regularity or context that children could rely on to derive meaning. The mind must provide meaning entirely on its own.

Notice, from **Table 1**, that the complexity of reading has reached its peak by the end of 2nd grade. After this grade, it is simply a matter of becoming a fluent reader. In contrast, conceptual challenges for math keep piling on. For example, in 3rd grade, a whole new domain is introduced: multiplication and division. Unlike addition and subtraction, these operations are not grounded in everyday language, thus requiring a certain level of abstractness. Furthermore, these operations come with a set of procedures and routines that need to be followed precisely. The mind also needs to attain a certain fluency in these procedures – one that interferes with the fluency acquired for addition and subtraction. Finally, the fluency in multiplication and division cannot be achieved through the gradual removing of a scaffold, but requires studious memorization – all enormous challenges for the mind (e.g., Welsh et al., 1991; Zelazo and Müller, 2002).

Then comes 4th grade – and with it a whole slew of conceptual challenges of abstraction, precision, and fluency. In this grade, children need to master fractions, which requires nothing less but to re-learn the very meaning of a number. Prior to fractions, numbers referred to whole quantities. Now numbers refer to either the number of parts (numerator) or the total number of parts (denominator). Both meanings must be accessible smoothly, and they must be understood in relation to each other. The challenge continues with decimal numbers and negative numbers (5th and 6th grade): Numeric symbols change in meaning because of a miniscule detail (e.g., [*2.0*] vs. [*0.2*]; [*2-*] vs. [*-2*]). The location of something as little as a decimal point, or of something as little as a negative sign, decide on the meaning of a number.

Consider, by contrast, what it takes to make sense of printed material. Individual letters appear in stable configurations that have largely unique meanings. For example, the word [*duck*] largely means [*duck*], no matter what context it appears in. When a word has more than one meaning, as is the case for homophones or metaphoric expressions, a readily available context will disambiguate the meaning. Rather than having something as miniscule as a dot to provide meaning, the entire sentence is available to give clues. There are ambiguities, of course (e.g., in [*The old man the boat*], [*man*] is used unexpectedly as a verb and [*old*] is used unexpectedly as a noun). But these ambiguities are exceedingly rare, and the larger context of the story often provides the necessary clues to generate meaning.

Taken together, we have shown that the nature of math is likely to be very challenging for the mind, namely from the very beginning, and exceedingly more so with every new grade. This is attributed to the need for fluency; the need for abstraction that changes with the context; the need for attention to detail, miniscule as the detail might be; the need to keep in mind different meanings and switch between them fluidly; and the need for relational reasoning. This analysis of math content (vis-à-vis reading content) should make it abundantly clear that math competence depends crucially on practice, more so than reading competence. It is even possible that a lack of sufficient math practice could conceal the source of a math learning difficulty. Thus, the shortage of research in this area is likely to be a problem for the field of math education. It is urgent to investigate math practice and how it can be done most effectively. In the next section, we turn to this question, focusing specifically on the barriers to math practice and how they can be overcome.

Math Practice: What Does It Take?

What kind of practice is most beneficial? The American Academy for Pediatrics (AAP) encourages parents to read with their children long before children reach the age of formal schooling (American Academy of Pediatrics News [AAP], 2014). Once school starts, there are multiple ways in which children are encouraged to practice, for example, through library memberships. Indeed, the 2013 report of the Pew Research Center found that 70% of interviewed parents visited a public library with their child in the past 12 months. Furthermore, 55% of children owned their own library card, and 87% of children's visits to the library ended in children borrowing a book. Even without family support, many schools have their own libraries to provide children with exposure to reading materials and make reading practice attainable. Formalizing these efforts, many schools have adopted the Accelerated Reader program to further encourage and track reading practice (Stefl-Mabry, 2005).

Furthermore, the AAP (2014) recommends for parents to establish a daily reading routine and allow children to choose the books themselves. Along the same lines, the Accelerated Reader program encourages children to choose their own books and work toward personalized reading goals (Renaissance Learning, 2016). The idea is that individualized practice, carried out frequently and in the context of a positive experience, is likely to strengthen reading competence (e.g., Nunnery et al., 2006). This approach agrees with the theoretical models of learning motivation, namely to provide children with mastery, autonomy, and purpose (Pink, 2011). Reading at one's own skill level allows students to feel competent; being able to choose the reading material allows for a high degree of autonomy; and the joy that is part of reading provides purpose to the activity.

A very different picture emerges with math practice. There is no general call for students to practice math at their own level. Instead, math practice is largely confined to school assignments and prescribed homework. The content and pace of such formal practice is dictated by the curriculum, leaving students little choice. For example, students are expected to complete all math problems on their worksheet or homework, by a deadline, and they are judged on their performance. The consequences of this state of affairs is much worse for students who are already behind in math. Having to work on something that is above their competence level is likely to lead to a negative experience and rob students of a sense of purpose and mastery (e.g., Slavin and Lake, 2008; Re et al., 2014; Kucian and von Aster, 2015).

An alternative is to encourage students to practice math at home, mimicking the initiatives for self-guided reading, over and above homework. However, this is likely to face substantial practical barriers: It is rather difficult to orchestrate self-guided practice and encourage children to carry it out.

An adult would need to develop practice problems that have the appropriate difficulty level for the child. The adult would also need to provide meaningful feedback to the child, to allow for discovery of potential gaps in the required skills. On top of that, the adult would have to provide a positive context and motivate the child to practice math. Together, this provides a substantial time investment and competence of an adult.

Apps on touch-screen tablets might be a viable solution: practice problems are already pre-determined, they are delivered in a playful format, and they provide instant feedback – all without the time investment of a trained adult (e.g., Kyanka-Maggart, 2013; Warman, 2014; Hilton, 2016). For instance, Kucian et al. (2011) found that 8- to 10-year-olds, instructed to practice math at home for 15 min a day, 5 days a week for 5 weeks, showed improved performance compared to pre-test performance. The likely benefit of computer-assisted interventions to support math competence has made it become more embedded in the educational context (e.g., Fuchs et al., 2006; Räsänen et al., 2009; Burns et al., 2010; Kesler et al., 2011; Kucian et al., 2011; Stickney et al., 2012; Doabler and Fien, 2013; Gross and Duhon, 2013; Jansen et al., 2013; Kanive et al., 2014). Here, we seek to expand these efforts and look at whether online apps are conducive to IMP.

We chose the math app IXL.com, without necessarily endorsing it over and above any other practice programs (see commonsensemedia.org, for other math practice apps). The IXL app currently has approximately 5.6 million school licenses and 400,000 family licenses in use (IXL staff, personal communication, October, 2016). It provides extensive opportunity to practice math skills relevant to the Common Core, ranging from pre-K basics to high school pre-algebra, algebra, and pre-calculus. This continuity in math skills makes it possible to find the appropriate difficulty level for a child, independent of grade level, background information, or motivation. Math practice problems are organized by grade, math topic, and problem sets. And each problem set features an example problem to facilitate the decision about what to practice. The setup delivers encouraging feedback when a math problem is solved correctly, it uses a point system that advances like a video game, and it downplays mistakes. When children make a mistake, the app provides a brief explanation of the concept, allowing children to learn from their mistakes, if they so choose.

Overview of Our Study: A Community-Based Participatory Research Approach

Our specific approach followed the design of community-based participatory research (CBPR). This approach emphasizes that research activities are decided upon in partnership with community agencies, namely to meet the needs of the community and maximize the likelihood that the activities benefit their members (e.g., Minkler and Wallerstein, 2003). Even though CBPR is rare in the context of math learning, it offers unique strengths to feasibility studies. CBPR allows the research to consider real-life complexities, including the presence of multiple stakeholders, as well as their unique constraints, priorities, and challenges. Such complexities often pose substantial hurdles for experimental results to be translated into a viable program and implemented on the ground – even very promising experimental results. CBPR makes it possible to anticipate these hurdles and help find ways to circumvent them.

At the same time, CBPR is not without shortcomings. Most importantly, the details of the methods are not entirely up to the researchers. They are instead designed in collaboration with the community partners, considering the existing structures within the organization and the goals of the community. Consequently, the research activities at a site are unique, mapped onto the needs of the community and the realities on the ground, with far less regard for precise data collection, control groups, and randomization. To circumvent these shortcomings and obtain meaningful results, our strategy was to implement the same general intervention in more than one setting.

For the current purposes, we partnered with three organizations, all of them serving elementary-school children from low-SES communities (two elementary schools and one non-profit organization). The effect of SES on early math achievement has been explored widely (e.g., Griffin et al., 1994; Jordan et al., 2002; Tucker-Drob and Harden, 2012). Children from low-SES communities are unlikely to have broad and frequent access to touch-screen tablets (cf., Bradley et al., 2001; Galindo and Sonnenschein, 2015). This allowed us to establish math-practice feasibility for a population that might lack extensive familiarity with this medium.

Working together with community partners, four settings were used to introduce tablet-based math practice. The first setting was a weekly enrichment program with one-on-one mentoring. Our program took place during one of those enrichment events, to observe tablet feasibility in a large group of child–adult pairs. The second setting was a summer camp implemented with camp counselors and volunteers. Our program took place for approximately 40 min per week, for five sessions, the goal being to observe large-group feasibility when one-on-one pairing between children and adults was not possible. The third setting was an in-school tutoring program. Here, we integrated the tablet-based practice with ongoing paper-and-pencil practice, to understand how the tablet-based practice interfaces with traditional tutoring. Finally, the fourth setting was an after-school program, offered alongside after-school homework help. Here, our program was carried out exclusively with tablet practice, to explore voluntary attendance to a math-practice program.

Our general approach was to bring touch-screen tablets to each of the settings and to observe the behavior of children as they engaged in math practice. While adult volunteers were always present, whether for small group or one-on-one support, their role differed slightly from that of a tutor (cf., Fuchs et al., 2008, 2013). Volunteers were asked to merely encourage children, not actually provide didactic support. This was done to get a better sense of a child's spontaneous interaction with the tablets. Note that we did not look at the effect of tablet use on math competence, as this was not possible in the current study design. Nevertheless, our design provides an important window into the question of whether tablets with math apps are a feasible tool for math practice.

MATERIALS AND METHODS

Table 2 provides an overview of the settings used for our observational study, including the ways in which they differed as a result of our CBPR design. For each setting, iPad tablets were used and outfitted with the IXL math practice app. We used a bulk of 30 generic log-ins that were shared between children across the different settings. Adult facilitators were available to guide children's math practice and provide encouragement throughout the sessions. In what follows, we describe each setting, the students, and the math practice activities that were carried out at each setting.

Setting 1: Enrichment Program

Cohort

Students were 3rd, 4th, and 5th graders at risk of, or currently experiencing transient living situations (determined by the school). They participated in a weekly enrichment program, organized by a local nonprofit agency that serves youth experiencing homelessness. Its goal was to provide students with unique experiences throughout the course of the school year, namely by pairing them up with a college mentor during each meeting. Each enrichment event occurred weekly for 90 min, and our intervention took place during one of those enrichment events.

Math-Practice Intervention

The 90-min math-practice intervention was presented as 'Math Olympics', complete with team flags, score charts, and medals. There were four 'competitions' students were asked to participate in, namely addition, subtraction, multiplication, and division, the goal being to complete as many problems as possible within a certain amount of time. Student–mentor pairs were organized into teams, although each student–mentor pair worked on their own math problems on the tablet. Mentors were instructed to help students find a problem set that they could complete independently: not too easy and not too difficult. Then students were given a few minutes to practice, which allowed mentors to check whether their choice of problem was appropriately challenging. Once mentors were confident that they had chosen a good problem set for the students, the competition started. At the end of the competition, the team that won the most games received a prize and the other teams received smaller prizes for participation.

Setting 2: Summer Program

Cohort

Students were in grades K-6, ranging in ages between 6 to 11 at the onset of the program. The students were selected to be a part of a 7-week summer camp because they were at risk of, or currently experiencing homelessness (as determined by the program administrators). They were recruited from personnel within local homeless shelters and case managers of local schools. There was no charge to attend the summer program, and general attendance rate was about 70%. Students were organized into three groups of 20 to 25 students per classroom, based on their age. Each group had a teacher, an instructional assistant, and a college mentor to lead the group, in addition to a small group of volunteers who supported the program (3 to 5 per classroom).

Math-Practice Intervention

Our intervention took place once a week, for a total of five sessions of approximately 40 min per group. At the beginning of a session, students were given a tablet and told to start with a common problem set. This initial problem set was chosen in such a way that all children in a classroom could complete it, as per camp counselors and prior sessions. Once children completed the common 'warm-up', they were asked to find a problem set that was appropriately challenging for their level, with the help of adult facilitators. Overall, only minimal training was given to the facilitators; they were merely instructed to assist the students in finding problems that were tailored to their ability and to motivate the students during the session. Due to the high number of students (compared to the number of adults), student-adult pairing was not possible. Thus, students were typically in groups of five, with one adult per group. Sometimes, parents joined in as well, working one-on-one with their children.

Setting 3: In-School Program

Cohort

Students were 4th graders ranging in age from 9 to 11 at the onset of the program. All students attended an inner-city public school that serves families from disadvantaged communities: According to this school's most recent Ohio School Report Cards (2016), 99% of the students are considered economically disadvantaged, 97% of them are African-American, and only 14% of 4th-graders passed the state test in math. The setting was a tutor program held once a week for 45 min during school hours for students with

TABLE 2 | Overview of settings.

	(1) Enrichment Program	(2) Summer Program	(3) In-School Program	(4) After-School Program
Students	$N \cong 30$	$N = 111$	$N = 31$	$N = 19$
Age range	9–11	6–11	9–11	9–12
Duration	1 h	4 h	10 h	20 h
Attendance	Mandatory	Mandatory	Mandatory	Voluntary
Type of facilitation	One-on-one	Small group	One-on-one	One-on-one
Adults training	Minimal	Medium	Minimal	High

low performance in math (per teacher recommendation). Each student was paired up with a college mentor to work with. For each meeting, a work-sheet was provided and mentors were asked to help their student the way they see fit.

Math-Practice Intervention

Our intervention took place during the tutoring program. In addition to the work-sheets, college mentors were also given tablets with the math app. Students were asked to use the tablets to practice single-digit multiplication facts at the beginning of each session. The college mentors were also asked to find appropriate problem sets for the student. Specifically, they were told to work on worksheets administered by the school staff and switch to the tablet practice when the worksheet problems were either too difficult (i.e., they perceived the students to benefit from extra practice) or too easy (i.e., they perceived the student to benefit from more challenging problems).

Setting 4: After-School Program

Cohort

Students were in grades 4 to 7, ranging in age from 9 to 12 at the onset of the program. All students at this location attended an urban private school, where 85% of the students qualify for free or reduced lunch and the large majority of students are African American. The students were recruited to participate in this intervention due to a need for additional help with math (as determined by their math teacher). Many of these students attended an already existing after-school tutoring program.

Math-Practice Intervention

Our intervention took place alongside the existing tutoring program, offered on different days so as to not interfere with the ongoing homework help. Our intervention was offered twice a week during a 7-month period, and students had the freedom of choosing when to attend (once or twice a week). The students were paired one-on-one with a facilitator to practice. Facilitators were encouraged to assist students in finding problems tailored to their ability and to motivate the students during the session. Students received incentives for attendance, which included snacks during each session, as well as larger incentives when they reached attendance milestones. Prior to the onset of the program, facilitators participated in a 3-h training session focused on protecting children from harm; and they participated in a 2-h training session designed to help them interact with children.

Measures

Given the nature of this community-based participatory research project, settings differed in what kind of data could be collected to evaluate feasibility of the math-practice intervention (see **Table 3** for an overview). Use of data was approved by the institutional review board, following ethical guidelines for research. In what follows, we describe each of the measures and how they were analyzed, after which we turn to describing our findings, separately by setting.

Informal Observations (Used in All Settings)

Informal observations are an important part of community-based participatory research, making it possible to describe the impact of an intervention in ecologically valid ways (e.g., Malterud, 2001). Observations were carried out by the authors, all of whom have been trained in the best practices of observational research (e.g., on how to minimize reflexivity and preconceptions, and how to maximize transferability). Field notes served as basis for the qualitative analyses.

Systematic Observations (Used in Settings 2–4)

During each session, facilitators were asked to record the problem sets that a child worked on. Facilitators also recorded how the child felt after each session ("How do you feel about doing math today?"). A 5-point Likert scale was used, each level being conveyed with a line drawing of a face (e.g., happy face, sad face). We used two versions of this scale, one version assessing degree of happiness (ranging from feeling 'very sad' to 'very happy'), and another version assessing the degree of nervousness (ranging from feeling very nervous to not nervous at all). Each child was presented with only one type of scale. Results were analyzed in terms of the number of sessions children participated in the type of problems children worked on, and their rating of the sessions.

Math Attitude Survey (Used in Settings 3 and 4)

We developed a survey to assess children's attitudes toward math at the onset of our program. It included items on how they feel when they are asked to complete math problems, whether they picture themselves in a job that will involve a lot of math, and how they feel about their math skills (compared to girls, boys, or

TABLE 3 | Data collected, separated by setting.

	(1) Enrichment Program	(2) Summer Program	(3) In-School Program	(4) After-School Program
Informal observations	Yes	Yes	Yes	Yes
Systematic observations	No	Yes[1]	Yes[2]	Yes[2]
Math attitude survey	No	No	Yes	Yes
Math competence (T_5 and T_{10} of WJ IV)	No	Yes	Yes	Yes
Student exit survey	No	No	No	Yes
Facilitator exit survey	No	No	Yes	No
Teacher interview	No	Yes	No	No

Systematic observations differed in whether the 5-point Likert scale measured (1) the degree of happiness or (2) degree of nervousness. Math fluency and calculation competence was determined using standardized subtests from the Woodcock–Johnson IV battery.

others in general). We also asked them to report on their coping mechanisms when faced with a challenging math homework. In a series of yes–no items, five items were specifically geared toward coping behaviors that are productive (e.g., getting motivated; "Do you ask somebody for help?"), and five items were specifically geared toward coping behaviors that are negative (e.g., getting distracted; "Do you try to get out of having to do it?") The difference between the number of positive versus negative coping behaviors reflects the degree of successful coping strategies a student had (ranging from −5 to +5). Results were analyzed in terms of average responses across items. Regarding validity and reliability, this measure is still under psychometric testing. For this reason, we treated each item individually, as single-item indicators, directly expressing the desired construct regarding a given attitude. Rather than report the findings as a math attitude "score," we merely counted the number of positive and negative items.

Math Fluency and Calculation Competence (Used in Settings 2–4)

To get a better sense of children's math skills, we measured math fluency and calculation competence, using two subscales from the Woodcock-Johnson test battery (Version IV). The subscale T_{10} measures math fluency with a 3-min-long timed test. It consists of two pages of simple operations with one-digit numbers, including addition, subtraction, and multiplication. The subscale T_5 measures a student's calculation competence. Students are instructed to do as many problems as they can until it gets too difficult, with no time limit. Items on this test range from simple operations (e.g., single digit addition, subtraction, etc.), to more difficult problems (e.g., multi-digit division, fractions, operations with negative integers, etc.) to advanced problems – too advanced for our purposes (e.g., logarithmic operations, calculus operations, etc.) Both subscales return the child's grade equivalent score. Results were analyzed in terms of average grade equivalence at the onset of the program (math fluency; calculation competence), as well as in terms of amount of change in these measures, from the beginning of the program to the end.

Student Exit Survey (Used in Setting 4)

We developed a survey to assess student perceptions of the program after it was completed. This was a standard satisfaction-type survey that directly probed expressed constructs. Our reporting of findings mirrors this, by simply reporting counts, and not a composite score for the exit survey. Students were told that their answers will be used only to gather information about the program and would not impact their grades or be shared with teachers or parents. The first part of the survey used open-ended questions about likes and dislikes of the program (e.g., "What did you like about the program?"). The second part had a series of items that measured children's beliefs about the program on a 3-point Likert scale. For example, children were asked to judge how much the program helped them with math (with the answer options being: "not very much", "a little bit", and "a lot"). The survey was one page long and took about 5 min to complete individually. Results were analyzed qualitatively, to get at children's experience of the program.

Facilitator Exit Survey (Used in Setting 3)

We developed a paper-and-pencil survey for facilitators, administered at the end of the intervention. This too was a satisfaction-styled survey with single items directly expressing given constructs. Facilitators were asked to rate the frequency with which they used the math practice app (compared to the paper-and-pencil worksheets used in this setting), and to describe the most common ways in which they used the app. Facilitators were also asked to describe the strengths and weaknesses of the math practice app and tablet use, and to provide suggestions for intervention improvement. Results were analyzed qualitatively, to shed light on the experience of facilitators.

Teacher Interview (Used in Setting 2)

We developed a semi-structured interview for teachers, administered at the end of the program, to examine teachers' thoughts and feelings about our tablet-based math intervention. The interview had three questions, but teachers were allowed to express new ideas and concepts outside of the line of questioning. First, teachers were asked "What are your thoughts on the math program?" Next, they were asked, "What works about the math program?" Finally, teachers were asked, "What would you change about the math program?" Each interview took approximately 10 min to complete. Field notes were used to record comments and were analyzed for themes. Results were analyzed qualitatively, to shed light on teacher experience.

RESULTS

Setting 1: Enrichment Program

Informal Observations

Results for this setting pertain merely to our informal observations, but they are nevertheless telling. Overall, students involved in this setting were visibly engaged in the math practice from start to finish. There were no behavioral problems, which is unusual for a size of about 30 students working on math. Additionally, students were able to use the tablets and the math practice app with minimal instruction, pointing to the user-friendly design. At the end of the session, the organizers of the enrichment program commented on the positive behavior and engagement of the students while practicing math. One of the organizers even stated that you could hear 'the drop of a needle' because the students were so focused during the session. Thus, this setting provided the first indication that tablet-based math practice has the potential to engage young children and motivate them to practice math. Given this success, the organizers of the enrichment event invited our team to implement our intervention in their summer program (Setting 2).

Setting 2: Summer Program

Informal Observations

Students were often quite excited when we arrived to their classroom and tablets were handed out. Many worked silently and diligently during the practice, showing no difficulty with using the tablet and the app. Despite the little amount of supervision and instruction, the students could navigate the app and tablet, and they worked independently throughout the entirety of the session. At the same time, there were some challenges, most notably since there were far more children than facilitators. Some of the older students were bored with the problem sets that were chosen at the onset of a session, while younger students were overwhelmed with the chosen problem set. Students had difficulty finding problems that are appropriately challenging, and even facilitators sometimes struggled with what to practice next.

Systematic Observations

Students attended between one to five sessions, with the average attendance rate being 2.75. Students in Grades 1 and 2 typically worked on counting and picture-based addition problems. Students in Grades 3 and 4 typically worked on addition, subtraction, and multiplication. And students in Grades 5 and 6 typically worked on multiplication and fraction problems. Students in all grades usually reported that the sessions they participated in were either fun or super fun, with only 14 students ever reporting that the session was either ‘bad’ or ‘super bad’ (which is less than 5% of the responses). This high level of reported enjoyment was confirmed by our observations.

Math Fluency and Calculation Competence

Students performed largely at grade level when entering the summer program. First-grade fluency was even above grade level. However, students 3rd grade and older often performed below grade level, especially for math fluency (being about one grade level behind). While calculation competence for older grades was typically at grade level (on average), there was very high variability in individual student scores, far higher than was observed for the younger students. Older children therefore are more strongly in need of a math intervention. Across the summer program, almost all the younger children improved in math fluency (82%). However, only approximately half of the older children did so (52%). In terms of calculation competence, only the first-graders improved as a group (by half a grade level on average). All other averages were lower at the end of the program, compared to at the onset. While these findings cannot be attributed to our intervention (positive or negative), they are nevertheless informative in terms of the challenge that comes with what a successful program needs to accomplish to counter the summer learning loss (cf., Cooper et al., 1996).

Teacher Interview

Teacher responses were in line with our observations. They noted the benefits of tablet learning, even for children who were known to have behavioral problems or math learning difficulties. Given that children differed significantly in their math ability in this setting, teachers expressed the importance of children working at their own skill level and at their own pace, without being pressured to perform at the level of other students in the class. Teachers also mentioned structural issues that provided a challenge to the tablet intervention, including the Wi-Fi connectivity. Even so, all teachers advocated for the tablet intervention to return in the next summer due to the reportedly outstanding results they felt it had on the students.

Setting 3: In-School Program

Informal Observations

Students were visibly eager to begin their session with single-digit multiplication practice using the math app on the tablets. However, multiplication was a challenge for some of the students, and those weakest in math would sometimes get frustrated. In these instances, the facilitator would intervene and move them to something simpler, often single-digit addition. Students were often reluctant to put the tablets away when it was time to work on the pencil-and-paper worksheets, and they would frequently ask to switch back to the tablet. Especially when the worksheet was too easy or too difficult, students often went back to the tablet, working on problems that were either more challenging or simpler than the worksheet. In one instance, a child completed a worksheet on calculating rectangular area and perimeter within a few minutes. Rather than continue to work on material that was not challenging or engaging, the facilitator found a problem set on the tablet for calculating area and perimeter of more complicated shapes.

The tablet was also used to target specific weaknesses that were leading to further problems. For example, when difficulty in rounding decimals was traced to a lack of understanding place values, one student was directed to a problem set that focused specifically on identifying place values. The student had been struggling with rounding decimals for numerous weeks, but it took only one session of math-app practice to master this skill. Overall, students were observed to benefit from the tablets in ways that would have been difficult to address with class-wide paper-and-pencil practice.

Systematic Observations

Students used the tablets for an average of 5.56 sessions. The most frequently reported type of tablet practice was multiplication (75%), followed by fractions (24%). When asked how students felt about a session, a large majority of children (81%) reported ‘not nervous’ on all of the sessions.

Math Attitude Survey

All students reported liking at least some part of math. However, almost half of them reported disliking some part of math (43%), and over a third of them reported to be at least somewhat nervous when having to do math (36%). Many children hoped to get a job that involves a lot of math (75%), and they consider themselves to be good or very good at math (75%). Interestingly, over half of the children believed they are worse than girls in general (55%), compared to being worse than boys in general (28%). In other words, for this group of children, girls were more likely to be perceived as math competent than boys. In terms of coping strategies, the average degree of successful coping was 2.82, with only three children obtaining a score of 0 or below (i.e., reporting no more motivating than distracting behaviors). One child obtained a score of 1 (i.e., reporting 5 motivating and 4 distracting behaviors). All other children (86%) obtained a score of 2 or higher, with four children obtaining a perfect score of 5 (reporting only motivating and no distracting coping behavior).

Math Fluency and Calculation Competence

The average grade-equivalent score for math fluency was 4.1 (based on 23 4th-graders), and the average grade-equivalent score for calculation competence was 3.4 (based on 24 4th-graders). Thus, while students performed at grade level on fluency, they were behind on calculation competence. At the end of the program, only about half of students improved (44% for math fluency and 50% for calculation competence). Again, this finding (whether positive or negative) cannot be attributed to the tablet practice exclusively. After all, these children participated in daily math instruction during school, and thus should improve in math fluency and calculation competence, with or without the tutoring program. These post-test results are nevertheless included here to highlight the challenge of math learning for children who are already behind in math.

Facilitator Exit Survey

The following attributes were used to describe the strengths of the app: the app was convenient (45%), the app was exciting or fun to the students (30%), the app provided immediate feedback (25%), the tablets engaged or interested the students (15%), and the app motivated the students (5%). Facilitators also stated that students preferred practicing on the tablets compared to practicing using the worksheets. The weaknesses reported by the facilitators were that the students' preference to work on the tablet distracted them from the worksheets (35%) and that there were problems related to technology glitches and Wi-Fi connectivity (25%).

Setting 4: After-School Program

Informal Observations

Initial student buy-in to this program was a significant challenge. Throughout the first few weeks of this intervention, our team often had more facilitators than children present. Once children became more aware of the program and got to know the facilitators, more children became involved on a consistent basis. In fact, many students formed distinct bonds with the adult facilitators. However, consistent student attendance remained a challenge throughout, as this intervention was not offered within a program students were already attending. Over the course of our intervention, improvements could be observed in overall student engagement, attendance, and performance. For example, one student initially experienced extreme difficulty engaging in math practice. The student would often merely guess on problems and present little affect to the facilitators and the program in general. By the end of this program, however, the student began expressing excitement toward the app and even math practice in general. In fact, the student said to the facilitator, "Come on already, I want to practice some math!" This transformation in student behavior and attitude was a common narrative for many students, pointing to the potential benefit of IMP.

Systematic Observations

Student attendance in this setting was voluntary and highly variable, ranging from one to sixteen hours of participation ($M = 6.8$). Students overall felt that the sessions were fun or super fun (80%). The most commonly practiced subject was multiplication (28%), followed by fractions (23%) and addition (16%).

Math Attitude Survey

Many students stated that they liked at least some math (79%), while almost half of the students reported disliking at least some math (42%). About half of the students stated that they felt happy or super happy when it was time for math (53%) and about a third of the students reported that they would feel happy or super happy if they would never have to do math again (32%). Almost half of the students reported that they would like to have a job that requires a lot of math (47%), and almost half of the students thought that they were good or very good at math (53%). More students believed girls are good or very good at math (63%) compared to boys (42%). In terms of coping strategies, the average coping score was 3.36, the lowest score being 0 (one student), and only one student obtaining a score of 1 (reporting 4 positive coping strategies and three negative coping strategies). All other students obtained a 2 or higher (90%), with one student obtaining a perfect score of 5 (thus reporting 5 positive coping strategies and no negative coping strategies).

Math Fluency and Calculation Competence

At the onset of the program, all students performed below grade level on calculation competence (100%), and over half of them performed below grade level on math fluency (55%). Students' scores improved at the end of the program, but more so for calculation competence than math fluency. Specifically, post assessments revealed that on average students improved more than half a grade level on calculation competence, with over half of them improving more than one grade level (55%). For fluency, only two students improved more than half a grade level.

Student Exit Survey

Eleven of the students felt that the program helped them either a little bit or a lot with math. The students also reported that they enjoyed staying after school to attend the program, and 89% of the students stated that they would participate in the program again. When assessing what they enjoyed about the program through open response, comments included: "I like how if I messed up they would push me to try again," "[The program] made math fun, they made everything fun" and "[The program] taught me math and raised my grade."

Summary of Results

Students enjoyed the tablet-based format and often became actively engaged in solving the math problems. For example, most students reported that sessions were either "fun" or "super fun" (Settings 2 and 4). Students did not feel nervous to practice math on the tablets (Setting 3), and they explicitly commented on how much liked the program (Setting 4). Furthermore, many students believed that the intervention helped them improve their math skills (Setting 4). Increases in standardized math scores lend support for this sentiment. Teacher perceptions of the program underscore the benefit of tablet-based learning and the individualized method of practice (Setting 2). And facilitators described the tablet-based practice as convenient to implement and fun for the students (Setting 3). Challenges pertained to dealing with occasional frustrations of students and with establishing long-term practice. Finally, both teachers and facilitators indicated structural issues of Wi-Fi connectivity as a significant challenge.

DISCUSSION

The impetus for our study came from what we refer to as the math-practice gap: IMP is far less prevalent in discussions of academic support than informal reading practice. While reading practice is promoted through libraries and the nation-wide Accelerated Reader program, math practice is confined to a formal context of curriculum-based learning. There is also very little research on math practice, leaving many questions open, including the kind of math practice that is needed, how to promote it, who to target, for how long to carry it out, and how to interface it with other education activities. The current paper is an initial step to begin this conversation, looking specifically at the feasibility of tablet-based math practice.

As discussed in the introduction, math practice faces far more challenges than reading practice. Specifically, math is exquisitely challenging for the mind, far more than reading. The mind needs to fluidly switch between different meanings of one and the same symbols, cued by the smallest of prompts. Given such difficulty, large individual differences are likely to occur (e.g., Berch and Mazzocco, 2007), with some children needing more help than others. As a result, large-group practice becomes problematic, leading to a spiral effect of less competent students falling further behind. Yet, an individualized math program is time-consuming to prepare: an adult needs to create math problems that are tailored to the competence of each child, correct the math problems the child solved, and provide meaningful feedback (Kucian et al., 2011). It does not help that children who are already behind in math – those who need math practice most – might be least likely to enjoy math practice.

We hypothesized that tablets with math apps could be a medium by which to address the math-practice gap. Using a CBPR design, the current study is a first attempt to look at whether such tablets are feasible for low-SES elementary-school children. The CBPR approach does not allow for the precise control of variables. For this reason, several different settings were used that incorporated tablets. In each case, children were given a tablet outfitted with the math app IXL. Differences in settings pertained to the amount of time children spent with the app, the number of children present, the number of adult volunteers present, whether they had a choice for alternative activities, and whether attendance was voluntary. Results show that the app was highly engaging for children, not a single student reporting difficulty with the mechanics of using the tablet. Across all settings, whether during a one-time event or in a year-long program, virtually all students were continuously willing to practice math, often deeply engaged in math practice, and showing very few behavioral problems. When students had a choice to practice math with the tablet or on a paper-and-pencil worksheet, they preferred the tablet.

The efforts required on the part of the adults were minimal. Facilitators were largely naïve to math education, and, far from being experts in math, they often commented on their own struggles with math. The training we provided varied from a brief 2-min introduction to the program to a multi-hour mandatory training. Yet, facilitator success was similar across the board. For example, one-on-one facilitators who had the least training (Setting 1) did not report any more problems than one-on-one facilitators who had the most training (Setting 4). Even parents and family members who came in to work with their students (Setting 2) could support their student's math practice, despite only having a brief introduction to the program and the app. Thus, the tablet-based practice was exceedingly easy for adults to supervise. At the same time, there were important caveats with the tablet-based math practice – most notably with how to promote long-term adherence which will be discussed next.

The most obvious challenge of the tablet-based practice is the cost associated with its use. This includes not only the cost for tablets and their maintenance, but also the fee for the app and the cost to maintain a reliable internet connection. For the current study, we provided a tablet and app for each student. Even so, we ran into difficulty with internet availability in all four settings. A slow internet connection led to aggravation on the part of the students, and sometimes we were required to abandon math practice on the tablets all-together. Once we left a setting, taking along the tablets, there was no alternative for the children to continue the IMP. A substantial investment in infrastructure would be needed to make tablet-based math practice a reality.

We found that the tablets and the math practice app provided reliable engagement for students to complete math problems. Thus, short-term motivation was high, once students got started. However, long-term motivation was more difficult to instill. In the after-school setting (Setting 4), where it was up to the child to attend the program, adherence issues became most obvious, with several children attending no more than three times throughout the year. Students often commented on the pressure they felt having to complete their homework, thus lacking the time to do extra math practice. Given that the tablet-based practice was not integrated with ongoing school activities, many students objected that is was not relevant to the required school work. In other words, even though the app led to a substantial amount of math practice once students started, the relation between the informal-practice progress and school work progress was not obvious to students.

Ultimately, math practice has little intrinsic motivation, other than the pleasure of one's own progress (e.g., being able to complete a problem set). Students in our study were often quite sensitive to how far they had fallen behind and what it would take for them to reach grade-level competence. These motivational aspects stand in sharp contrast to informal reading practice, which allows students to choose a story from a vast array of stories. Even students who fall behind in reading can enjoy a story, likely to be unaware of how long it would take to reach grade-level competence. It is clear that intrinsic motivation for math practice needs to be increased, maybe by using a reward system that is similar to the Accelerated Reading Program.

Given that math practice has very little intrinsic appeal—despite the use of the app and tablets—we explored various ways to encourage adherence via reward. This included playful competition (Olympia competition during the one-time enrichment of Setting 1), snacks upon completion of a problem set (Setting 2 summer program), or prizes at the end of the program (Setting 3 after-school program). While these initiatives had some positive effects, measurable success is likely to be limited. Instead, main motivation appears to have been supplied by the adult volunteers. In fact, when the student-adult ratio was one-to-one (Settings 1, 3, and 4), math practice worked best (judging by children's engagement). In contrast, in the settings in which there were many more children than adults (Setting 2), some behavioral problems became apparent.

Recall that adult volunteers were instructed to refrain from trying to convey math concepts to the students. This includes refraining from explaining a wrong answer and from working on the math problem for them. The facilitators' task was instead to merely help students find an appropriately challenging problem set and motivate them to complete it (or help them adjust the challenge level, as needed). The outcome was a successful partnership where children were motivated to complete their math. Telling were our observations in the program that was carried out during school hours, when students were partnered one-on-one with adults (Setting 3): The tablet was perceived as an effective practice tool, both by the students and the tutors. It remains to be seen what it takes to improve motivation when a one-on-one facilitator setting is not possible.

Would it help to integrate informal tablet-based practice with ongoing school activities? Such integration would allow students to see their tablet practice translate into success during homework or graded assessments, rather than a mere add-on. Of course, this can be a challenge too, given that some students need more practice than others. If students would be assigned math practice that is too difficult for them, or if it would take them too long to become proficient at a concept, the positive effects of the practice are likely to fade. A better option might be to start math practice early in a child's schooling, before large gaps appear, and instill a commitment to individualized math practice that is ongoing and independent of reaching a specific goal. Future work must determine if this recommendation holds up empirically.

CONCLUSION

Our observations across four settings show that elementary-school students were highly engaged in the tablet-based math practice. This is impressive on several grounds. First, children who underperform in math might try to avoid math practice, certainly when it comes to practicing outside of formal schooling. Indeed, many of our students scored below grade level at the onset of our program, yet they often looked forward to our intervention. Second, many of the children who participated in our program reported negative attitudes toward math, something that should further increase resistance to IMP. The tablet and math app allowed them to practice math despite these attitudes. Thus, our study is a first step to demonstrate that tablets with math apps can be a feasible way to deliver sorely needed math practice, thus a way to address what we had coined as the "math-practice gap". While our data do not speak to the relative efficacy of different aspect of the math intervention, our findings provide an important impetus for further investigating tablet-based math practice.

ETHICS STATEMENT

This study was carried out in accordance with the recommendations of the guidelines of the Institutional Review Board, with written informed consent from all subjects. All subjects gave written informed consent in accordance with the Declaration of Helsinki. The protocol was approved by the Institutional Review Board of the University of Cincinnati.

AUTHOR CONTRIBUTIONS

SS designed and carried out two of the four settings outlined in the paper, outlined the first draft of the final paper, and edited as the paper was developed. MC and ZA each designed and implemented one of the four settings, contributed to the first draft of the final paper, and edited the paper as it was developed. JC was involved in the design and implementation of two of the settings, as well as the drafting and editing of the final paper. HK contributed to the design, implementation, and well as oversaw all four of the settings, assisted in the drafting of the paper, and all edits involved.

FUNDING

The authors received financial support from an internal grant through the University of Cincinnati (awarded to HK and JC) to purchase the tablets and the IXL licenses that were used in this project.

ACKNOWLEDGMENTS

The authors would like to thank members of the Children's Cognitive Research Lab for their assistance with the data collection, transcribing of the data, and data analyses. Additionally, we would like to thank the schools, organizations, administrators who facilitated our interventions.

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Conflict of Interest Statement: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

frontiers in Psychology

ORIGINAL RESEARCH
published: 08 February 2017
doi: 10.3389/fpsyg.2017.00144

Touchscreen Tablets: Coordinating Action and Perception for Mathematical Cognition

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Proportional reasoning is important and yet difficult for many students, who often use additive strategies, where multiplicative strategies are better suited. In our research we explore the potential of an interactive touchscreen tablet application to promote proportional reasoning by creating conditions that steer students toward multiplicative strategies. The design of this application (Mathematical Imagery Trainer) was inspired by arguments from embodied-cognition theory that mathematical understanding is grounded in sensorimotor schemes. This study draws on a corpus of previously treated data of 9–11 year-old students, who participated individually in semi-structured clinical interviews, in which they solved a manipulation task that required moving two vertical bars at a constant ratio of heights (1:2). Qualitative analyses revealed the frequent emergence of visual attention to the screen location halfway along the bar that was twice as high as the short bar. The hypothesis arose that students used so-called "attentional anchors" (AAs)—psychological constructions of new perceptual structures in the environment that people invent spontaneously as their heuristic means of guiding effective manual actions for managing an otherwise overwhelming task, in this case keeping vertical bars at the same proportion while moving them. We assumed that students' AAs on the mathematically relevant points were crucial in progressing from additive to multiplicative strategies. Here we seek farther to promote this line of research by reanalyzing data from 38 students (aged 9–11). We ask: (1) What quantitative evidence is there for the emergence of AAs?; and (2) How does the transition from additive to multiplicative reasoning take place when solving embodied proportions tasks in interaction with the touchscreen tablet app? We found that: (a) AAs appeared for all students; (b) the AA-types were few across the students; (c) the AAs were mathematically relevant (top of the bars and halfway along the tall bar); (d) interacting with the tablet was crucial for the AAs' emergence; and (e) the vast majority of students progressed from additive to multiplicative strategies (as corroborated with oral utterances). We conclude that touchscreen applications have the potential to create interaction conditions for coordinating action and perception into mathematical cognition.

Keywords: attentional anchors, touchscreen tablet, mathematics, proportional reasoning, sensorimotor interaction

OPEN ACCESS

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Specialty section:
This article was submitted to Developmental Psychology, a section of the journal Frontiers in Psychology

Received: 15 July 2016
Accepted: 20 January 2017
Published: 08 February 2017

Citation:
Duijzer CACG, Shayan S, Bakker A, Van der Schaaf MF and Abrahamson D (2017) Touchscreen Tablets: Coordinating Action and Perception for Mathematical Cognition. Front. Psychol. 8:144. doi: 10.3389/fpsyg.2017.00144

INTRODUCTION

Educational theory should offer valuable heuristics for designing applications that foster students' conceptual learning. However, these theories have by and large focused on learning-with-*paper* rather than learning-with-*technology* (Papert, 2004). This theory-to-practice gap is particularly acute in the case of touchscreen tablets: Whereas tablets offer a breakthrough in human-computer interaction by way of enabling direct multi-touch manipulation of virtual objects, educational research is still scarce on how performing motor actions can contribute to the development of conceptual knowledge (Glenberg, 2006; Marshall et al., 2013; Abrahamson and Bakker, 2016). Even when researchers do engage students in multimodal interaction, where action and perception are elicited as cognitive entry into target concepts, these actions and perceptions are rarely studied via multimodal learning analytics (Worsley and Blikstein, 2014). Consequently, critical data are lost on how action and perception may lead to more advanced reasoning. In the current study we investigated how students could benefit from engaging with an interactive tablet application designed to foster mathematical reasoning through the development of new sensorimotor coordination.

Investigating multimodal learning could be especially beneficial in those learning domains in which students are known to experience severe difficulties. Proportional learning is one such area. It could be that students' difficulty with developing proportional reasoning lies not so much with the mathematical concepts *per se* as much as with their conventional presentation, which is as symbolical expressions of quantitative relations. Symbolic presentation of mathematical concepts, particularly without guiding students in the appropriate multimodal animation of the symbols, is liable to elicit inappropriate understandings, for example it may evoke additive routines where multiplicative solutions are needed. In the current study we use an interactive touchscreen tablet application (MIT-Ext), an extended version of the *Mathematical Imagery Trainer for Proportion* (MIT-P; Reinholz et al., 2010; Abrahamson et al., 2011) that was inspired by arguments from the theory of embodied cognition that mathematical concepts are grounded in sensorimotor schemes (e.g., Varela et al., 1991). In this application students move their fingers up and down along two vertical bars to try and make the bars green. They will be green, rather than red, only when the respective heights of the bars relate by a preset proportion, such as 1:2, that is initially unknown to the students (see **Figure 1**). These physical movement patterns students learn to enact could potentially create opportunities to ground what will become the target mathematical content of proportionality.

The current study was designed to investigate the emergence of sensorimotor schemes as students engage in a MIT-Ext task. We hypothesized that while students' hands move the bars at a constant ratio, their eyes will follow dynamical patterns. These patterns are called attentional anchors (AAs) – psychological constructions of new perceptual structures in the environment that people invent spontaneously as their heuristic means of guiding effective manual actions for managing an otherwise overwhelming task (Liao and Masters, 2001; Hutto and Sánchez-García, 2015; Abrahamson and Sánchez-García, 2016). **Figure 2** demonstrates an AA that occurred frequently in the empirical data.

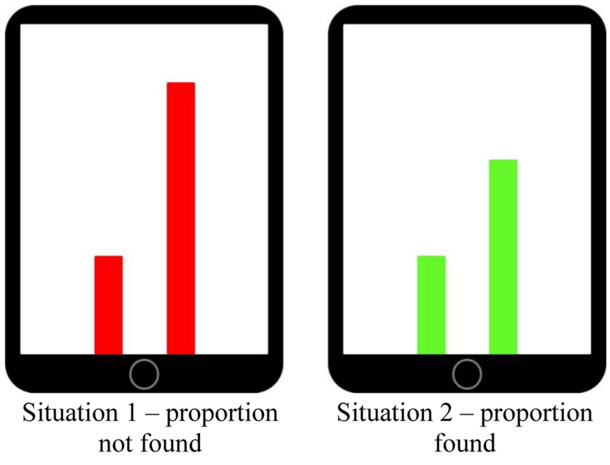


FIGURE 1 | Representation of the MIT-Ext colored bars. Both bars have to be moved in parallel motion. Once the right proportion is found (example: pre-set proportion 1:2), the bars will turn green.

Prior studies from this research program showed that throughout the task, students often looked at specific parts of both bars and their eyes moved in patterned sequences among these locations. The conjecture arose that these perceptual behaviors consistently predicted students' conceptual transition from additive to multiplicative strategies (Shayan et al., 2015; Abrahamson et al., 2016). In the current study we examined in detail the process of constructing AAs so as to determine how these perceptual structures facilitated students' motor actions in accord with the task demand that is, moving the virtual objects while keeping them green. In particular, we describe how the coordination of action and perception stimulated students' progression from additive to multiplicative solution strategies. We articulated the following two research questions to guide this new line of inquiry:

(1) *What quantitative evidence is there for the emergence of AAs?*
(2) *How does the transition from additive to multiplicative reasoning take place when solving proportion tasks in interaction with the touchscreen tablet app?*

In the next section we focus on the theoretical rationale and design methods for investigating embodied-interaction technologies for learning mathematics, and in particular learning proportions.

THEORETICAL BACKGROUND

Proportional Learning

For primary school students proportion is a notoriously difficult domain of mathematics. In the Dutch school system, the

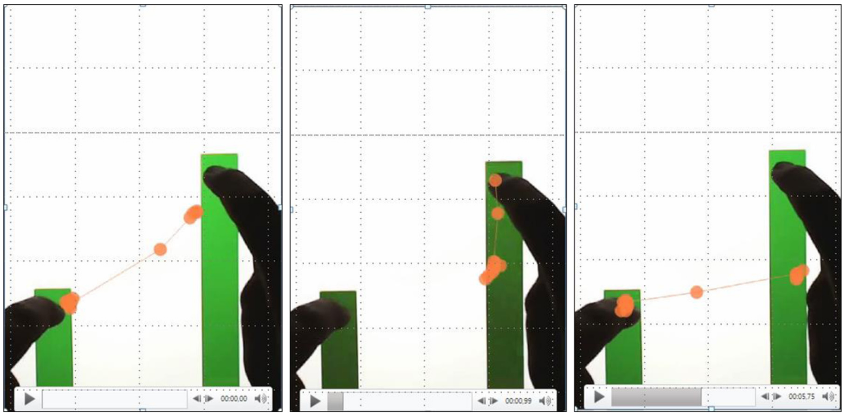


FIGURE 2 | Three consecutive video stills overlaid with eye gaze data, showing the occurrence of a perceptual triangle, whereby the student looks at the top of the short bar, top of the high bar and halfway up the high bar.

domain "proportions, fractions and percentages" enters the school curriculum in the late elementary grades. Students have to meet particular standards related to ratio and proportion. These standards are set in the so-called Reference Levels Arithmetic (CITO, 2013) and are assessed by a student tracking system and in national examinations (Boswinkel and Schram, 2011). Before the age of 12, Dutch students have to get a sense of the structure and consistency of quantities, whole numbers, decimal numbers, and percentages. Moreover, they should be able to do some (context-bound) calculations with those mathematical objects (CITO, 2013). During the teaching of proportion there is an emphasis on working with a ratio table, which either is given to students or they must recognize when it might be useful (Van Galen et al., 2005). As such, there is a large emphasis on applying learned rules and strategies instead of developing a deep understanding of proportion.

Essentially, proportional learning involves understanding the multiplicative part-whole relations between rational quantities. This means that a change in one quantity is always accompanied by a change in the other, and that these changes are related by a constant multiplier (Piaget and Inhelder, 1966/1977; Lamon, 2007; Boyer and Levine, 2015). Proportional reasoning and the ability to conduct multiplicative operations can be seen as an important precursor for virtually all other mathematical content, including concepts such as ratios, fractions and linear functions (Karplus et al., 1983; Vergnaud, 1983; Lesh et al., 1988; Bakker, 2014). Despite the paramount importance of proportionality, mastering it remains a challenge for school curriculum (Tourniaire and Pulos, 1985; Lamon, 2012). In particular, students experience difficulty in developing fluency with proportions that build upon – yet are differentiated from – simpler non-multiplicative concepts (e.g., additive constructions), notations, terminology, and procedures (Karplus et al., 1983; Tourniaire and Pulos, 1985; Lamon, 2007; Fernández et al., 2012).

Students' progression from additive strategies to multiplicative strategies can be seen as a central component of their growing proportional understanding. Additive and multiplicative strategies are theorized in different ways. The current study follows the work of Carpenter et al. (1999), Van Dooren et al. (2010), and Abrahamson et al. (2014), in eliciting the sequences discernible in the students' emerging proportional learning. Additive strategies on the one hand wrongly focus on the additive differences between components of the ratio (1:2 = 3:4 because 1 + 1 = 2 and 3 + 1 = 4) and on the other hand correctly on repeated addition (1:2 = 3:6, because 1 + 1 = 2 and 3 + 3 = 6), while multiplicative strategies draw on the internal ratio of similar units and apply these to other units (1:2 = 3:6, because 2 = 2*1 and 6 = 2*3).

With respect to the development of proportional reasoning a crucial question then is how students *ground* multiplicative conceptualizations of ratio in additive conceptualizations of proportions (Abrahamson et al., 2014) and how this can be supported by making use of interactive touchscreen tablet applications (e.g., embodied learning tasks).

Embodied Cognition as a Theory for Mathematical Cognition

In its most fundamental form embodied cognition theory states that the mind, body, and its surrounding environment are highly interrelated, and hence, mutually dependent upon each other (Wilson, 2002; Anderson et al., 2012). In this view, human cognition is deeply rooted in the body's interactions with its physical environment, where (motor) action, perception and cognition are intricately linked, and reasoning consists of reproducing fragments of embodied experiences (e.g., Lakofff and Nùñez, 2000). This opposes views of early mainstream cognitive science epistemology where the mind is seen as an information processing system, operating completely separately from the body's sensorimotor systems. Per that view, reasoning (including mathematical thought) is non-bodily, timeless and universal, and the formation of concepts is not restricted by physical realities. And yet proponents of the embodiment view conceptualize, cognitive processes and (mathematical) concepts not as abstract but rather as fully embodied, emergent phenomena (Núñez et al., 1999).

Many studies have provided empirical evidence for the embodied nature of mathematical cognition, including the role of the body in appropriating mathematical concepts. For example, in their study on students' gestures and the embodied knowledge of geometry, Kim et al. (2011) investigated how gesturing facilitated the emergence of mathematical knowledge, by embodying the multisensory properties underlying geometrical concepts. They found that students' gestures influenced their thinking about geometrical concepts. Moreover, as the geometrical concepts became more complex, the gestures the students deployed became more complex as well, indicating an intricate relation between gesturing and mathematical knowledge formation. Similar results with respect to the embodiment of mathematical thinking and learning were found by Wright (2001), Broaders et al. (2007), and Alibali and Nathan (2012). Another study by Lozada and Carro (2016), investigating Piagetian conservation tasks in students, found that making students active participants in the transformation process, instead of letting them merely observe the same phenomenon, would help them recognize quantity invariance. These studies, among others, suggest that cognition can be a direct consequence of sensorimotor experiences of conceptual exemplars, which indicates that there is a formative relationship between bodily experiences and mathematical concepts (Johnson-Laird, 1983; Malinverni et al., 2012). The guiding principle is that even the most abstract mathematical concepts are in fact grounded in sensorimotor experiences (Núñez et al., 1999; Wilson, 2002; Gallese and Lakoff, 2005) and created by the human imaginative mind via a very specific use of everyday bodily grounded cognitive mechanisms, such as conceptual metaphors, analogical reasoning, or fictive motion (Miller and Johnson-Laird, 1976; Núñez et al., 1999; Lakofff and Nùñez, 2000; Wright, 2001). Following this embodiment perspective, it is thus important that students are offered the appropriate embodied experiences from which to construct these key concepts. However, these are rarely included in current educational practices. For example, when solving problems involving proportions such as, "1:2 = 3:[?]," students cannot *experience* the meaning of proportional *equivalence* as indicated by the " = " symbol, since they do not have a structured opportunity to enact, visualize, or conceptualize certain number pairs (Abrahamson and Lindgren, 2014).

One promising approach, capable of facilitating the emergence of sophisticated schemes mobilizing mathematical learning and development, are embodied-embedded instructional technologies – including touchscreen tablets – (Black, 2010; Antle, 2013), which incorporate and enable students' emerging sensorimotor enactments and visualizations of mathematical concepts (Reinholz et al., 2010; Abrahamson et al., 2011). Certain technologies are based on the premise that directing people to move in specific patterns of action may guide and improve comprehension, problem solving, and learning (e.g., Fischer et al., 2011; Antle, 2013). As such, students can develop pre-symbolical mathematical cognition by engaging in embodied activities that create the right opportunities to build particular action–perception schemes related to proportions. In particular, we present an example of a learning environment designed with the intention that students first develop proportional sensorimotor schemes and later progressively formalize these schemes in the form of mathematical discourse.

As such, by coordinating action and perception students could move from informal goal-directed motions to more formal mathematics, following a concurrent shift from additive toward multiplicative reasoning. Thus the design and evaluation of an interactive technological device for mathematical learning created an empirical context to pursue broader research problems pertaining to the cognitive process of developing quantitative proportional reasoning. Here we are interested in the interplay between action and perception when students work on the touchscreen application described above. Using eye-tracking technology, we evaluate the construct of AAs and its explanatory power to illuminate hidden processes in our findings related to students': (a) dynamical patterns in visual attention to the objects; (b) hand movement; and (c) reasoning following changes in visual attention.

Eye-Tracking to Identify Attentional Anchors

An AA, in essence, is an action-oriented perceptual configuration overlaid onto a problem space (e.g., the nearby environment to which people guide their attention). It can take many forms, depending on the properties of a task and the domain in which the task is going to be carried out. For example, a juggler might imagine a geometrical structure (e.g., a rectangle) hovering in the air in order to coordinate his actions. Accordingly, an AA can be seen as a real or imagined object, area, or other *aspect* or *behavior* that co-exists in a person's perceptual manifold. In other words, AAs can be thought of as a geometrical form overlaid onto the perceived world and functioning as a tool by which one could coordinate their sensorimotor actions (Liao and Masters, 2001; Abrahamson and Sánchez-García, 2016).

Abrahamson et al. (2016) hypothesized that AAs are constructed and used for motor-action coordination when solving the MIT-Ext tasks. They suggest that the AA play critical roles in achieving both the activity's primary goal of performing the motor action per task specifications and the secondary goal of mathematizing the physical solution strategy. With respect to the tasks used in our study, from an embodiment perspective, there is the assumption that students develop action-perception coordination schemes to tackle the target problem. We expect students to act out goal-directed movements while looking at mathematically relevant areas in the touchscreen task (i.e., top of the bars and halfway the tall bar). Moreover, since the goal of the task is largely unknown for students at the start of the task, it is expected that students first deploy exploratory haphazard eye-movements, and thereafter, when patterns and task-goals are becoming clear, deploy more deliberate and patterned eye-movements directed at the task relevant areas (Haider and Frensch, 1999; Rayner, 2009).

In the present study we want to further investigate the interaction of action-gaze-reasoning behavior by looking into the eye-measures, including fixation count, fixation duration and scan path of the AA patterns, as well as the timing of the AA patterns and how all these relate with the effective solution strategies. In order to elucidate these (mainly) implicit processes, eye-tracking measures are supplemented with concurrent thinking-aloud transcripts (Van Someren et al., 1994). We assume that the combined use of both methodologies will provide us with a more detailed understanding of the hidden and fine-grained aspects of a participants' perceptual and cognitive processing (Van Gog et al., 2005; Rayner, 2009; Hyönä, 2010; Lai et al., 2013; Van Gog and Jarodzka, 2013).

MATERIALS AND METHODS

Participants

Forty-five fifth- and sixth-graders from five elementary schools in the Netherlands voluntarily participated in the study. The schools were all denominational, where families were predominantly white and from middle class backgrounds. Seven participants were excluded from the analysis, due to technical problems; four had incomprehensible audio, two had unclear dark video, and one had mis-calibrated distorted eye-measures. The 38 remaining participants were included in the analyses (21 male, 17 female; $M_{\text{age}} = 135.37$ measured in months, $SD = 8.37$). Before data gathering commenced, the ethical committee board of the faculty of Social Sciences at Utrecht University approved the study (2015). Additionally, informed consent was obtained from the legal guardians of all students involved.

Materials

Task in MIT-Ext

The task in MIT-Ext consists of two colored vertical bars. For each bar a student can use their index finger to move the bars up and down. Moving the bars in parallel motion changes the color of the bars along a gradient between red and green. The bars can be set at a predefined ratio (e.g., 1:2, 2:3, 3:4, *etc.*). The bars will *only* turn green when the student finds the *correct* proportion. For example, with the pre-set proportion 1:2, the right bar (RB) has to be twice as high as the left bar (LB). In order to keep the bars green, one has to move their fingers at a pace relative to this pre-set proportion. The aim of the task for the participant is to find *the mystery rule* that causes the bars to turn green (i.e., the pre-set ratios). Eye-tracking technology was added for multimodal data-gathering. MIT-Ext exists of an interface that allows the user to pre-set multiple tasks. The present study included one task, with a pre-set proportion of 1:2. The task consists of three phases, wherein after the first phase, in which the screen is plain white, symbolic artifacts are being added onto the environment (i.e., a grid in phase 2 and a grid supplemented with numbers in phase 3) intended to scaffold a learner's conceptual understanding of proportions. For a schematic overview of the task and the included phases, see **Figure 3**.

The students were consistently guided through the environment (Abrahamson et al., 2011, 2014) by following an instruction strategy (i.e., providing cues, e.g., "Try to make the bars green, and maintain the green bars even when you move your hands").

Eye-Tracking Equipment

Eye-tracking data were collected using a Tobii X2-30, mounted on a stand designed for eye-tracking research with mobile devices (e.g., smartphones, tablets). An external camera captured the scene by making video recordings (including audio) during task processing. These recordings were exported to the Tobii software (Tobii, version 3.3.0) to be integrated with the gaze data.

Coding Scheme for Video Data and Thinking-Aloud Transcripts

For the analysis of participants' video data and thinking-aloud transcripts, a coding scheme was developed. The transcripts were coded on the utterance level and consisted of one dimension *knowledge articulation*, divided over two categories (a) *knowledge content*, and (b) *solution strategy*. The first category, *knowledge content* was developed by Chi (1997). Chi's coding scheme differentiates between unique contributions (C), repetitions of previous contributions (R) and no problem content at all (0) and as such can be seen as a vital part of *knowledge articulation*. Additionally, since the verbally strong participants might have an advantage over the verbally weak participants (Chi, 1997), it seemed reasonable to differentiate between utterances that were contributions and utterances that were repetitions (of previous contributions), including only the contributions into subsequent analyses.

All the *contributions* of the previous category were coded on the second category, solution strategy (Abrahamson et al., 2014). The second category entailed seven 'strategy' codes, being: (1) *pre-additive*, (2) *fixed interval*, (3) *changing interval*, (4) *a*-per-*b*, (5) *a*-per-Δ, (6) *multiplicative*, and (7) *speeds*. Short descriptions of the codes with examples are provided in **Table 1**. In essence, within these solutions strategy codes the development of students' additive conceptions into a more sophisticated multiplicative framework can be traced, following the literature into proportional learning and reasoning (Carpenter et al., 1999; Misailidou, 2007; Reinholz et al., 2010; Van Dooren et al., 2010), but cannot be seen as an ordinal scale in itself. For example, deploying a "speeds" solution strategy is not necessarily *better* or more *advanced* than performing a "multiplicative" solution strategy.

Since these sensorimotor enactments were conveyed in essentially the same dynamical hand gestures (i.e., moving the bars simultaneously while keeping the bars green can be interpreted as an enactment of the *a*-per-Δ solution strategy as well as an enactment of the multiplicative solution strategy), the choice was made to primarily rely on the reasoning utterances of the students, while looking at the video data. Moreover, qualitative observations in previous studies into the same tablet application showed that students' solution strategies preceded or coincided their motor enactments of these strategies (Shayan et al., 2015, 2017). Short descriptions of these motor enactments can be found in **Table 1**. In addition, in the current study, a *pre-additive* code was also included, which is not directly related to a specific sensorimotor enactment, but instead, has a more exploratory nature. During this pre-additive strategy students search for early clues as to why

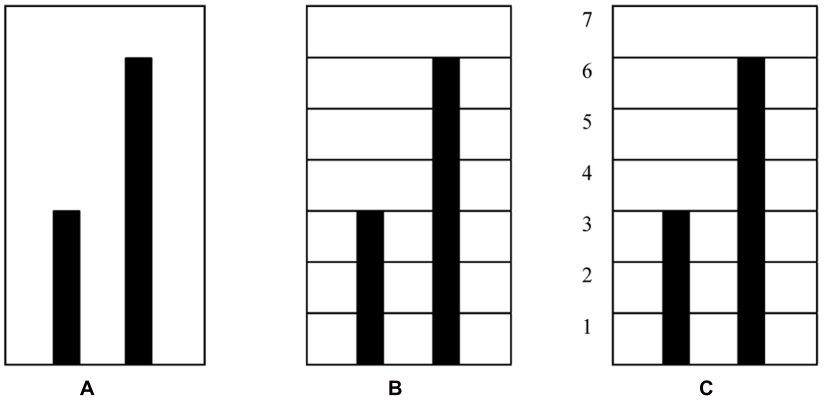


FIGURE 3 | Schematic representation of the three phases within the task: (A) pre-set proportion 1:2, blank screen; **(B)** pre-set proportion 1:2, grid; **(C)** pre-set proportion 1:2, grid supplemented with numbers.

TABLE 1 | Characteristics and examples of the two dimensions in the codebook for the video and verbal data.

Dimension	**Characteristics**	**Description/Example**	
Knowledge articulation			
(1a) *Knowledge content*			
Contribution (C)	Refers to utterances that are indicative of a student's emerging proportional reasoning.	'My right hand has to move faster than my left hand to keep it green.'	
Repetition (R)	Refers to repetition of previous contributions.	'When I move faster with my right hand, it remains green.' [*repetition of the utterance above*]	
Null-content (N)	Contains no problem content at all.	'Can I start already?'	
(1b) *Solution strategy (from additive to multiplicative reasoning)*[a]			
		Conceptual strategy	**Motor action**
Pre-additive (1)[b]	Comments are focused on the visual appearance of both bars.	'Right should be higher than left.'	Random movements, green is being found based on chance.
Fixed interval (2)[b]	Students try to maintain a constant spatial interval between both hands/bars.	'There is a difference of two, so I have to go up two at both bars.'	The difference between both bars is being held constant.
Changing interval (3)[b]	Students modify the spatial interval between both hands/bars in order to enlarge the distance.	'The higher I go, the bigger the distance needs to be.'	The difference between both bars is being enlarged.
a-per-b (4)[b]	Student deploys sequential hand-movements, each hand moves up or down according to its respective quota.	'For every unit left, I go up two unit's right.'	Both bars descend or ascend at respective constant values.
a-per-Δ^c (5)[b]	Student deploys a strategy that attends to the interval between the left- and right-bar as it changes with respect to the height of the lower bar.	'1–2 is one line apart, 2–4 is two lines apart, 3–6 is 3 lines apart.'	When the left bar rises, the right bar rises by one unit more than the previous difference between both bars.
Multiplicative (6)[b]	Quantitative statements about the numerical location of one of the bars directly as a product of the numerical location of the other bar.	'The right bar is twice as high as the left bar.'	A value is determined for the left bar, which is continuously doubled to find the value for the right bar.
Speeds (7)[b]	Statements are about the relations between both bars in terms of their respective velocity.	'My right hand has to go faster than my left hand, in order to keep both bars green.'	Both bars ascend and descend at different constant velocities.

[a]*The given examples are based on pre-set proportion 1:2.* [b]*Used ordering of the strategies in brackets, the ordering of the used solution strategies was based on the literature into proportional development (e.g., Misailidou, 2007; Van Dooren et al., 2010; Abrahamson et al., 2014). Furthermore, following Abrahamson and Sánchez-García (2016), 'speeds' was interpreted as a simultaneous enactment of the a-per-b strategy while at the same time can be interpreted as a qualitative indication of the multiplicative solution strategy.* [c]Δ *= Magnitude of interval between hands.*

the bars turn green (Reinholz et al., 2010). For a detailed account – and previous use – of the solution strategies in a similar context, see the study of Abrahamson et al. (2014).

Procedure

Pilot Studies

Two pilot studies were conducted in order to test the methodological outset of the main study. During the first pilot study, the MIT-Ext application and the instruction strategy were tested. Four students (age range: 7–10 years) performed several tasks on the MIT-Ext (set-proportions 1:2 and 2:3). For these students the pre-set proportions were difficult. Based on this first pilot study, and following previous research on embodied mathematical learning (e.g., Reinholz et al., 2010; Abrahamson et al., 2011; Petrick and Martin, 2012) and proportional development (Piaget and Inhelder, 1966/1977; Siegler and Pyke, 2013), it was decided to only include students between the age of 10 and 12 years (grade 5–6). A second pilot study was conducted with four students (age range: 11–12 years). Here the pre-set proportions 1:2 and 3:4, and the instruction strategy were tested. Based on this second pilot study it was decided to set the pre-set proportion for the task to 1:2, and to make the instruction strategy more elaborate in order to ensure consistency.

Thinking-Aloud Instructions

Following the standards described by Ericsson and Simon (1993), students were encouraged to think-aloud during task performance in order to connect their gaze-data with their proportional reasoning. They were instructed in two ways: (1) written, in the start screen of the task itself and (2) verbally by the researcher. With respect to the environment, a piece of text was incorporated into the MIT-Ext application, twice ("do not forget: say everything you think, out loud to the researcher"). Moreover, whenever necessary throughout the duration of the task, the researcher instructed the students to verbalize everything that came to their minds.

Semi-structured Clinical Interviews

The students took part in individual sessions of approximately 1 h during the day in a separate room at schools. At the beginning of each session students got written instructions on the tablet screen, together with images, explaining how to interact with the app: "You have to move the bars up and down and find the green bars. Try to keep the bars green while moving them." First students were allowed to explore the environment in order to find *as many greens they could*. During this exploratory phase the researcher did not explicitly ask them to express their thoughts. Only when students found the first green, the researcher asked them to find *more greens*. This first phase roughly took 2–5 min (the time students spent per phase and on the whole task varied considerably between students – range in seconds: [419–1475]). After the first exploration phase the students were probed to articulate their thoughts regarding what they were doing and which actions they were undertaking in order to find the *mystery rule*. Regardless of their rule articulation at the end of the first task phase (i.e., blank screen) the students were asked to move the bars all the way up from the bottom to the top while keeping the bars green. After this first phase the previously mentioned instructional probes were repeated throughout the other task phases (i.e., grid and grid supplemented with numbers) as well, while also encouraging the students to express their thoughts about *why the bars turned green* to gain more insight in their used solution strategies. At the end of the third phase the students again were asked to move the bars all the way up. During the task the researcher repeated pre-formulated sentences, such as: *"Can you find more greens?"* and *"Could you tell me what you are doing right now?"* These consecutive interaction periods primed the interview data for subsequent analyses and comparison.

Eye-movements, screen recordings and concurrent verbalizations were captured during the entire task performance. Verbalizations by the students were transcribed verbatim.

Data Analysis

Verbal Transcripts

The coding of utterances was done with a computer program designed for the coding of qualitative data: MEPA (version 4.10) (Erkens, 2005). Two raters familiar with the task and the materials as well as with the coding scheme scored 7.5% of the transcripts ($n = 3$). Inter rater reliability computed on this subsample of transcripts yielded a Cohen's κ of 0.88 for the knowledge content category, and a Cohen's κ of 0.73 for the solution strategy category, which both can be considered good. One rater scored the remaining transcripts.

Eye-Tracking Data

For the analysis of participants' eye-tracking data so-called 'areas of interest' (AoIs) were defined. These AoIs were selected based on the mathematical frameworks underlying proportions, which also make sense in the context of the used application (i.e., two bars set a pre-set proportion) (cf., Shayan et al., 2015; Abrahamson et al., 2016). Here it was assumed that students would make sense of the tasks by (1) looking from left to right and vice versa, (2) looking halfway both bars in order to see the shorter bar as halfway the taller bar, and (3) looking at both bars from the top to the bottom and vice versa in order to define the differences between the top of both bars and the bottom of both bars (cf. Fuson and Abrahamson, 2005; Boyer and Levine, 2015). Each bar was divided in three areas of the same size (allowing to gather eye-fixation and gaze data at the top of both bars, halfway both bars, and at the bottom of both bars). These areas would grow and shrink relative to the changes in the bars' height. Moreover, the area between both bars and the area outside both bars were included as two AoIs as well. **Figure 4** provides a schematic representation of the dynamic AoIs used in the current study.

Eye-tracking variables

Based on the literature into problem-solving and expertise development (e.g., Gegenfurtner et al., 2011; Susac et al., 2014), we included four eye-tracking variables in our analysis: (1) the sum of the *fixation counts* within each AA AoI divided by segment time (i.e., time that students seek the mystery rule), (2) the *average fixation duration per visit* by dividing *fixation duration* by *visits in AoIs* (fixation duration was the *total duration by which participants looked at a certain AoI* (in seconds), visits were defined as the successive entering and exiting of an AoI), (3) the *unique visits* by dividing the *visits* by segment time, and (4) the *scan path*, as a count measure, by which participants looked at several AoIs successively.

Besides fixation count, fixation duration, and visits within AoIs it was decided to incorporate the *scan path* because it

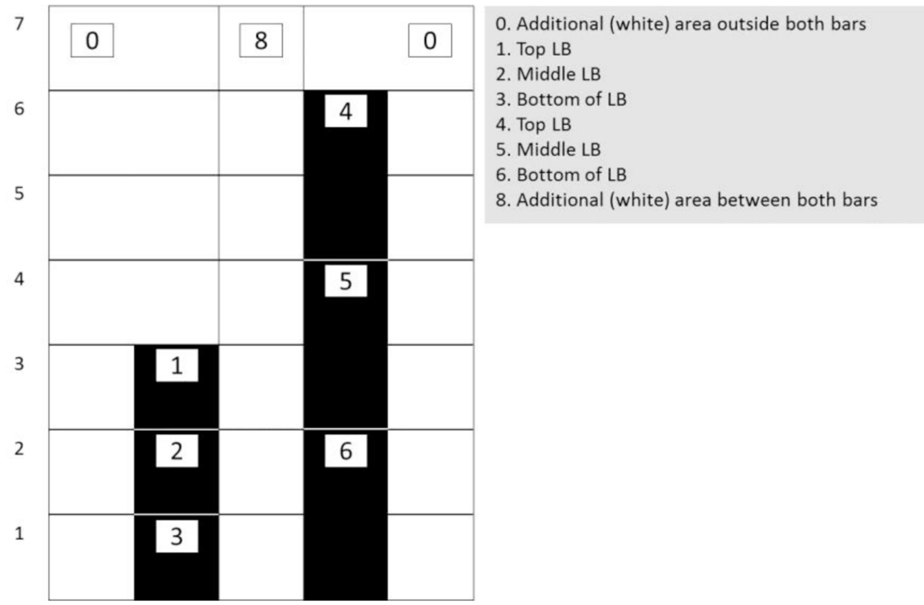


FIGURE 4 | Schematic representation of the allocation of the eight (dynamic) areas of interest (AoIs) used in current study. The AoIs on the bars were slightly larger than the bars: 40 pixels on both sides and 40 pixels on top.

includes fixation sequences, and gives information about multiple successive fixations and saccades (Holmqvist et al., 2011; Lai et al., 2013). Including the scan path gives insight into the complex patterns of eye movements when processing dynamic stimuli (Jarodzka et al., 2010). In the context of the task this would imply a deeper insight in student's subsequent eye-movements, and as such could give an indication of the specific eye-patterns that are of interest when solving proportion related tasks. Moreover, when looking at the research of Shayan et al. (2015), being able to quantify the eye-gaze patterns that might have a role in student's conceptual understanding of proportions is essential to push forward the research in this domain. As such, including the scan path as an eye-measure is insightful in describing the multitude of geometrical variations the AA might hold, and what if any is the role of AAs in the coordination of perception, action and reasoning when performing embodied proportional touchscreen tablet tasks.

Pre-processing

In order to process the eye-tracking data the raw gaze data was first filtered with the default Tobii fixation filter (Olsson, 2007). This filter identifies fixation points by a minimum of 5 gaze points grouped within a radius of 35 pixels. Moreover, before going through the recorded data, the Tobii fixation filter applies a correction to missing gaze data points below 100 ms. Using Tobii Studio the gaze data (within segments) was exported to Microsoft Excel. Additionally, using a matlab script the eye-coordinates were converted to the same coordinate system of the hand-coordinates from the apps' hand movement log files. This was necessary to manually calculate the fixation count and fixation durations of the AOIs with respect to the dynamic height of the bars. Another script was written with python programming language to calculate the fixation duration, visit count, and fixation count (Python, version 2.0; Python, 2015). As such, Python calculated for each time stamp with a fixation point, based on the position of the hands in that timestamp, the associated AoI of the gaze. Moreover, the dynamic track of the gaze data over the AoIs, was also recorded in this program and was returned as the scan path.

Analyses RQ 1 What Quantitative Evidence Is There for the Emergence of Attentional Anchors in Terms of Location, Fixation duration, and Scan Paths?

First, for every participant the segments of the eye-data that could be used were defined. It was chosen to focus on the moment between a student started to deploy specific eye-movements indicative of an AA (Shayan et al., 2015) till they articulated their first multiplicative rule (i.e., answering the question: "why do the bars turn green?"). Based on these segments, for every participant the *fixation count*, *fixation duration*, unique *visits* per AoI, and the *scan paths* over the AoIs were calculated. Descriptive statistics (i.e., frequencies and percentages) are reported to show which AoIs are attended to in terms of count, duration and visits. Next we looked at the scan path and calculated the most frequently occurring gaze sequences. This was done in two ways: (1) time-based, and (2) event-based. For the time-based method, per participant, all occurring patterns were divided by the same participant's time on task (in seconds). Subsequently, for each occurring pattern these values were added. As a consequence, every pattern got a score indicative of their frequency of occurrence in the sample. As a result, the five patterns with the highest score were picked and included. For the event-based method, per participant, the five most occurring patterns were located. Per participant, the pattern that occurred most got a score of five, the pattern that occurred second most got a score of four, until the least occurring pattern of the five most occurring patterns got a score of one. Subsequently, for each occurring pattern these values were added. As a consequence, every pattern got a score indicative of their frequency of occurrence in the sample. Again, the five patterns with the highest score were included.

Analyses RQ 2 How Does the Transition from Additive to Multiplicative Reasoning Take Place When Solving Proportions Tasks?

This second research question is being addressed by analyzing the interaction transcripts in MEPA, to gain a deeper insight into the transitions between the seven different solution strategies in order to detect whether students might show a progression toward more advanced strategies. As such, a lag-sequential analysis was done in MEPA to extract the transitions between solution strategies per participant. Since only the transitions between certain phases were of interest, all repeated consecutive solution strategies were excluded. For example, when a student mentioned the *a*-per-*b* solution strategy twice or more (as a unique contribution) directly after each other, this was changed to mentioning this solution strategy only once. Subsequently, frequency transition tables between all possible combinations of solution strategies were analyzed. Significant transitions are calculated based on a comparison between the observed frequency transition table and an expected frequency transition table where all expected transitions were defined. The values of both tables are then compared to each other to see whether the found transitions in the sample significantly deviates from those transitions one would expect based on chance. Furthermore, since the literature suggests that a transition from additive toward more multiplicative strategies are important indicators for proportional reasoning (e.g., Carpenter et al., 1999; Reinholz et al., 2010; Van Dooren et al., 2010), an aggregated file was made of the initial seven solution strategies into four overarching components, being: (1) *pre-ratio* (or proto-ratio), mostly incorrect strategies (e.g., students keep the distance between both bars fixed; 1:2 = 3:4) (the former pre-additive and fixed distance reasoning), (2) *additive* (the former *a*-per-*b*, and *a*-per-Δ reasoning), (3) *multiplicative* (multiplicative reasoning), and (4) *speeds* (the former change and speeds reasoning, which can be seen as a qualitative account of quantitative multiplicative reasoning). With these four categories it is possible to elucidate students' transitions from additive to multiplicative frameworks.

RESULTS

First, video and gaze data were inspected to identify the emergence of AAs. Based on qualitative inspections of video data, the exploratory study of Shayan et al. (2015) already showed that students tend to direct their gaze toward the top of the LB, top of the RB and halfway the RB (length of the LB on the RB), either distinctly or supplemented by separate switches in between those. This focus emerged without explicit instruction. This distinct eye-gaze pattern (AoI 1-4-5, see **Figure 2**) can be seen as indication of an AA. The current study adds to these insights by focusing on the moments before stating the rule of the task. Here students show similar visual patterns, indicating that accomplishing such perceptual-motor (eye-hand) coordination, enabled the students to develop strategies by which they kept both bars green. From this moment on, this distinct gaze pattern will be called a *gaze triangle* whenever necessary. Since the gaze triangle seems closely related to conceptual understanding (i.e., students show similar eye-gaze patterns around the moment they find the solution to the tasks), underscoring the assumption that there are critical phases in knowledge development, the first moments a similar AA appeared were located across the sample. Accordingly, segments were made in Tobii Studio, by which the start of each segment reflected the appearance of the AA for the first time. The end of the segment was marked 5 s after stating the rule of the task (e.g., the RB has to be twice as high as the LB). The moment the students show the first AA till they state the rule will be termed as the *critical phase*, whenever necessary. Subsequently, segments were exported in order to use them for data analysis.

Results Research Question 1

Table 2 gives information on students' eye-measures in terms of counts, fixation duration and number of visits in each of the eight AoIs. From this table it can be noticed that especially AoI 1, AoI 4, and AoI 5 are at the core of the students' attention, forming a gaze triangle. As such, AoI 1, AoI 4, and AoI 5 were more frequently and longer looked at and visited compared to others. These areas were top of the LB, top of the RB and middle of the RB.

Analyses of the occurrence of eye-gaze patterns (i.e., *scan paths*) show that the transition between 1 and 4 (not necessarily in this order) are most common when looking at two subsequent transitions, while the transition between 1-4-5 (not necessarily in this order) are most common when looking at three subsequent transitions. See **Table 3**, for the five most occurring two- and three-digit gaze sequences over the six AoIs. The five most occurring two- and three-digit gaze sequences are visualized in **Figures 5A,B**. Moreover, when looking more closely at the raw data files to see whether these patterns indeed were the most occurring patterns for every student individually, it was revealed that within the two-digit eye-movement patterns, pattern 1–4 was the most occurring pattern for a large portion of the students [60.53%], followed by pattern 4–5 [28.95%], and within the three-digit eye-movement patterns the most occurring patterns were 1-4-5 [73.68%], and 1-2-4 [13.16%], indicating that these eye-gaze patterns indeed were most frequent for most students in the sample.

In sum, manipulating both bars (i.e., performing a situated sensorimotor operatory scheme) in order to keep both bars green corresponded with distinct gaze patterns that students frequently deployed, when progressing through the touchscreen tablet task. Moreover, by acting out goal-directed movements students looked at mathematically relevant areas. In doing so they hooked their initial understanding of proportions to the mathematical structures underlying proportions as this was visually presented in the touchscreen tablet application. Overall, these quantitative results show evidence for the emergence and existence of AAs as was qualitatively observed in the video data.

TABLE 2 | Means and SDs of number of counts, fixation duration (in seconds), and number of visits in the eight AoIs [percentages given between brackets].

AoIs	Eye-measures					
	Counts		Duration		Visits	
	M [%]	*SD*	*M* [%]	*SD*	*M* [%]	*SD*
AoI 0	1541.89 [11.74]	1602.93	49.59 [13.58]	53.46	95.74 [14.28]	95.69
AoI 1*	**2680.95 [20.41]**	2844.17	**71.33 [19.54]**	63.51	**126.32 [18.84]**	109.86
AoI 2	500.26 [5.81]	521.75	16.94 [4.64]	16.98	28.32 [4.22]	25.54
AoI 3	274.24 [2.09]	356.49	7.75 [2.12]	10.83	15.74 [2.35]	16.55
AoI 4*	**4335.92 [33.01]**	4417.90	**114.67 [31.42]**	93.76	**183.68 [27.40]**	149.11
AoI 5*	**1382.76 [10.53]**	1219.66	**43.63 [11.95]**	30.01	**69.66 [10.39]**	52.76
AoI 6	499.53 [3.80]	527.94	15.76 [4.32]	15.92	25.53 [3.81]	24.17
AoI 8	1918.92 [14.61]	1562.14	45.30 [12.41]	31.03	125.32 18.70]	93.09

**Based on qualitative observation of the video data the AoIs indicative of the AA were 1, 4, and 5.*

TABLE 3 | The five most occurring (two- and three digit) eye-movement patterns over the six areas of interest (two ways of calculating: using time-based and event-based measures).

	1	2	3	4	5
Two-digit eye-movement patterns					
Time-based (occurrence)	1–4 (67.72)	4–5 (38.81)	1–5 (21.13)	1–2 (10.47)	2–4 (6.34)
Event-based (score)	1–4 (167.50)	4–5 (144.75)	1–5 (82.83)	1–2 (53.33)	2–4 (29.83)
Three-digit eye-movement patterns					
Time-based (occurrence)	1–4–5 (12.87)	1–2–4 (4.32)	1–2–5 (2.98)	4–5–6 (2.50)	2–4–5 (2.21)
Event-based (score)	1–4–5 (167.50)	1–2–4 (95.00)	4–5–6 (57.77)	1–2–5 (52.87)	2–4–5 (46.67)

Results Research Question 2

The solution strategies found in current sample are in accordance with the solution strategies outlined in the work of Abrahamson et al. (2014) that was based on video data without eye-tracking technology. **Figure 6** shows a schematic representation of the observed solution strategies in which the strategies and accompanying motor enactments are visualized and explained. Since an in-depth description of those strategies with examples is beyond the scope of this article; the 2014 article gives an elaborate account. In short, the figure shows the six solution strategies. For example, the *fixed interval* solution strategy is shown first. In black you see the first enactment, where the LB is one and the RB is two. Subsequently, the position of the bars change, visualized in blue and yellow (2:3 and 3:4). It is shown that the difference between both bars stays the same (fixed interval), which is incorrect when the pre-set proportion is 1:2.

Frequencies and Order of Students' Solution Strategies

All students in the sample used at least two different solution strategies. Some students used all solution strategies. **Table 4** provides an overview of the strategy occurrence frequencies of the students. Frequencies show that overall the use of solution strategies varies. The pre-additive and multiplicative strategies were used most often. When specifically looking at the solution strategies during the critical phase (i.e., showing the first AA till stating the rule in the first task), it is noticeable that the students used the a-per-b, a-per-Δ, and speeds strategy the least. **Table 5** shows the overview of transitions between two subsequent codes in the interaction transcript. All statistically significant transitions are presented with z-scores between brackets. Closer inspection of the values reveals that the students in our sample more often used a solution strategy further in the sequence after a solution strategy earlier in the sequence than vice versa (106 times vs. 48 times). Especially the transitions from pre-additive solution strategies to fixed solution strategies (10 times, $z = 3.93$), from pre-additive solution strategies to multiplicative solution strategies (20 times, $z = 3.24$), and from multiplicative solution strategies to speeds solution strategies (12 times, $z = 3.61$) seem to occur most.

Table 6 shows the aggregated solution strategies, and as such the transitions from incorrect toward correct strategies, from additive strategies toward multiplicative strategies, and from multiplicative strategies toward speeds strategies. The first thing to note is that there are significant transitions from (incorrect) pre-ratio solution strategies toward (correct) additive (12 times, $z = 2.40$), multiplicative (23 times, $z = 3.03$), and speeds (16 times, $z = 3.20$) solution strategies. Second, the transition from additive solution strategies to multiplicative solution strategies can be regarded as a significant transition as well (16 times, $z = 3.43$). Finally, as was already discernible in the previous table, there is a significant transition from multiplicative solution strategies to speeds solution strategies (16 times,

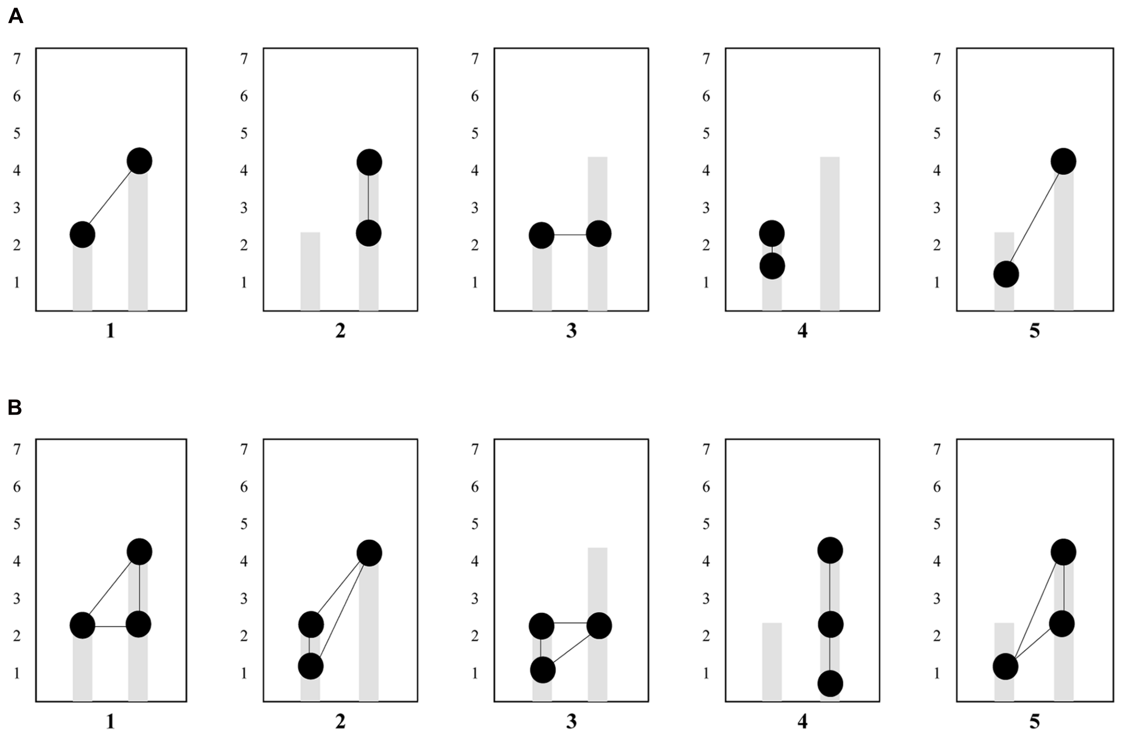
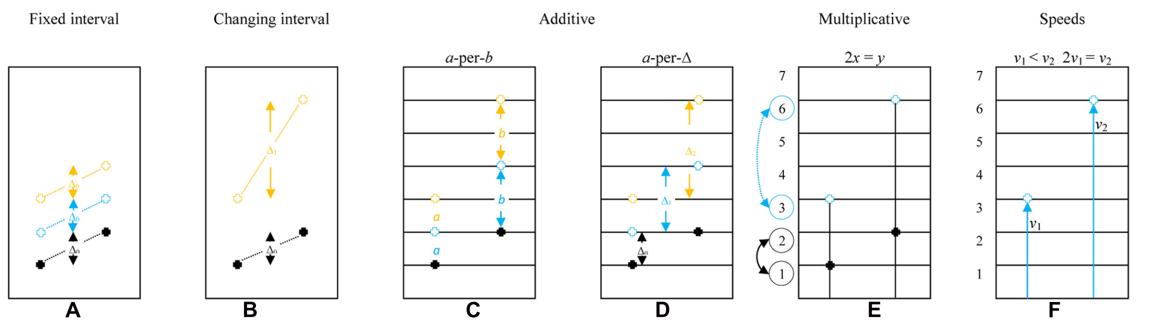


FIGURE 5 | (A) Overview of the two-digit gaze-patterns apparent in our sample. Circles connected by lines are representative of the gaze-patterns. Pattern 1 was most prevalent across participants. **(B)** Overview of the three-digit gaze-patterns apparent in our sample. Circles connected by lines are representative of the gaze-patterns. Pattern 1was most prevalent across participants.



Note on abbreviations: LB = left-bar; RB = right-bar; Δ = magnitude of interval between cursors (vertical and diagonal variants); *v* = velocity

FIGURE 6 | Adapted from Abrahamson et al. (2014). Student generated solution strategies for the make-the-bars-green problem (pre-set proportion 1:2): **(A)** fixed interval – maintaining Δ constant regardless of RB-and-LB elevation (incorrect solution); **(B)** changing interval – modifying Δ correlative to RB-and-LB elevation; additive, either **(C)** co-iterate composite units – both LB and RB ascend or descend at respective constant values *a* and *b* (*a*-per-*b*), or **(D)** LB rises by *a* (usually 1), RB by 1 box more than the previous Δ; **(E)** multiplicative – relocating the next green position as a function of the height of only one of the bars (given LB at *x* and RB at *y*, $2x = y$; $x = {}^{1}/_{2}\,y$), e.g., determining LB *y*-axis value, than doubling to find RB value, then halving for LB, and **(F)** speeds – LB and RB ascend/descend at different constant velocities ($v_1 < v_2$) or RB velocity is double LB velocity ($2v_1 = v_2$; $v_1 = {}^{1}/_{2}\,v_2$. LB, left-bar; RB, right-bar; Δ = magnitude of interval between cursors (vertical and diagonal variants); *v* = velocity.

$z = 2.34$), indicating that the students in the current sample often explicated their quantitative multiplicative insights by a qualitative speeds related account. For example, when a student mentioned a multiplicative solution strategy (e.g., "the RB always has to be half as tall as the LB"), this was more often elucidated by a speeds related solution strategy (e.g., "I have to move my right hand twice as fast as my right hand") than one would expect based on chance.

In the next section the findings of the previous sections will be clarified by giving qualitative examples of students' progression through the task.

TABLE 4 | Frequencies of solution strategies during the first (pre-set proportion 1:2) task, and during the critical phase.

	Pre-additive	Fixed interval	Changing interval	*a*-per-*b*	*a*-per-Δ	Multiplicative	Speeds	Sum
Tasks								
Task 1	33 (87)	12 (20)	17 (27)	20 (28)	7 (7)	38 (162)	15 (24)	142 (355)
Critical phase	30 (70)	10 (20)	12 (18)	7 (8)	4 (4)	38 (38)	3 (4)	104 (162)

Absolute frequencies are given (i.e., sum of the students who used that solution strategy). Total amount of used solution strategies are given between brackets. Note that time on task has not been taken into account.

TABLE 5 | Overview of the transitions between two subsequent solution strategies.

Code	1	2	3	4	5	6	7		Total T	Frequency of occurrence
(1) Pre-additive	–	10 (**3.93**)	9 (**2.95**)	1 (–)	2 (–)	20 (**3.24**)	2 (–)		40	44
(2) Fixed	1 (–)	–	5 (**2.75**)	6 (**3.32**)	3 (**3.09**)	4 (–)	0 (–)		18	19
(3) Change	3 (–)	0 (–)	–	5 (**2.25**)	0 (–)	8 (–)	4 (–)		17	21
(4) *a*-per-*b*	1 (–)	1 (–)	1 (–)	–	2 (–)	11 (-)	2 (–)		15	23
(5) *a*-per-Δ	0 (–)	0 (–)	1 (–)	1 (–)	–	4 (**2.50**)	0 (–)		4	8
(6) Multi	9 (–)	4 (–)	4 (–)	8 (–)	0 (–)	–	12 (**3.61**)		12	20
(7) Speeds	2 (–)	2 (–)	1 (–)	2 (–)	1 (–)	6 (–)	–		–	61
									106	
Total Transitions	16	7	7	11	1	6	–	48	154	196

Significant z-scores in bold between brackets, $p < 0.05$.

TABLE 6 | Overview of the transitions between two subsequent aggregated solution strategies.

Code	0	1	2	3		Total T	Frequency of occurrence
(0) Pre-ratio	–	12 (**2.40**)	23 (**3.03**)	16 (**3.20**)		51	51
(1) Additive	2 (–)	–	16 (**3.43**)	4 (–)		20	29
(2) Multiplicative	12 (–)	9 (–)	–	16 (**2.34**)		16	36
(3) Speeds	7 (–)	8 (–)	14 (–)	–		–	61
						87	
Total transitions	21	17	14	**–**	**52**	139	177

Significant z-scores in bold between brackets, $p < 0.05$.

Touchscreen Tablets: A Meeting Place for Action, Perception and Cognition – Two Qualitative Examples

The video data and think-aloud transcripts of two students were chosen to illustrate how touchscreen applications can be a meeting place for action, perception, and cognition. Whereas the previous results sections focus on the presence and frequency of appearance of any AA, and on the order and use of the different solution strategies, we here are integrating all these findings by giving two concrete examples of students progressing through the task. Here we show the variation and commonalities that exist between students. In short, a focus will be on (1) elucidating the findings of the previous section, by giving examples, and (2), elaborating on the cognitive processes (in terms of attention allocation and reasoning) taking place between showing the first AA and stating the rule. As such, these examples will give a fine-grained account of how action and perception are coordinated during emerging proportional reasoning.

Figures 7A,B show the students' developmental trajectories in terms of appearing AAs during the critical phase. **Figures 8A,B** show the students' sequences of solution strategies and progression through the entire task. For the first student, see **Figure 7A**, the moment showing the AA for the first time till stating the rule is relatively long. Student 1 articulated a multitude of solution strategies before stating his first multiplicative rule. In this respect, a few moments after the first AA was shown the student stated a strategy related to changing interval. After the articulation of this strategy he articulated a strategy related to fixed interval and a little later gives a qualitative account of the *a*-per-*b* solution strategy. From this latter strategy he gradually progresses into a multiplicative mathematical register (cf., Abrahamson et al., 2014), as shown in the following excerpt:

S1: "It is this piece here [*LB*], which I hold with my left hand [*student moves his left finger up and down the screen*], that should be added over there [*his gaze is focused on the top of the LB while switching to the top of the RB and between the top of the LB and the length of the LB on the RB*]."
[...]
R: "Can you show that to me?"
S1: "Well, for example, it is this part [*difference between both bars*], like this, when that part becomes higher, the bars turn green."

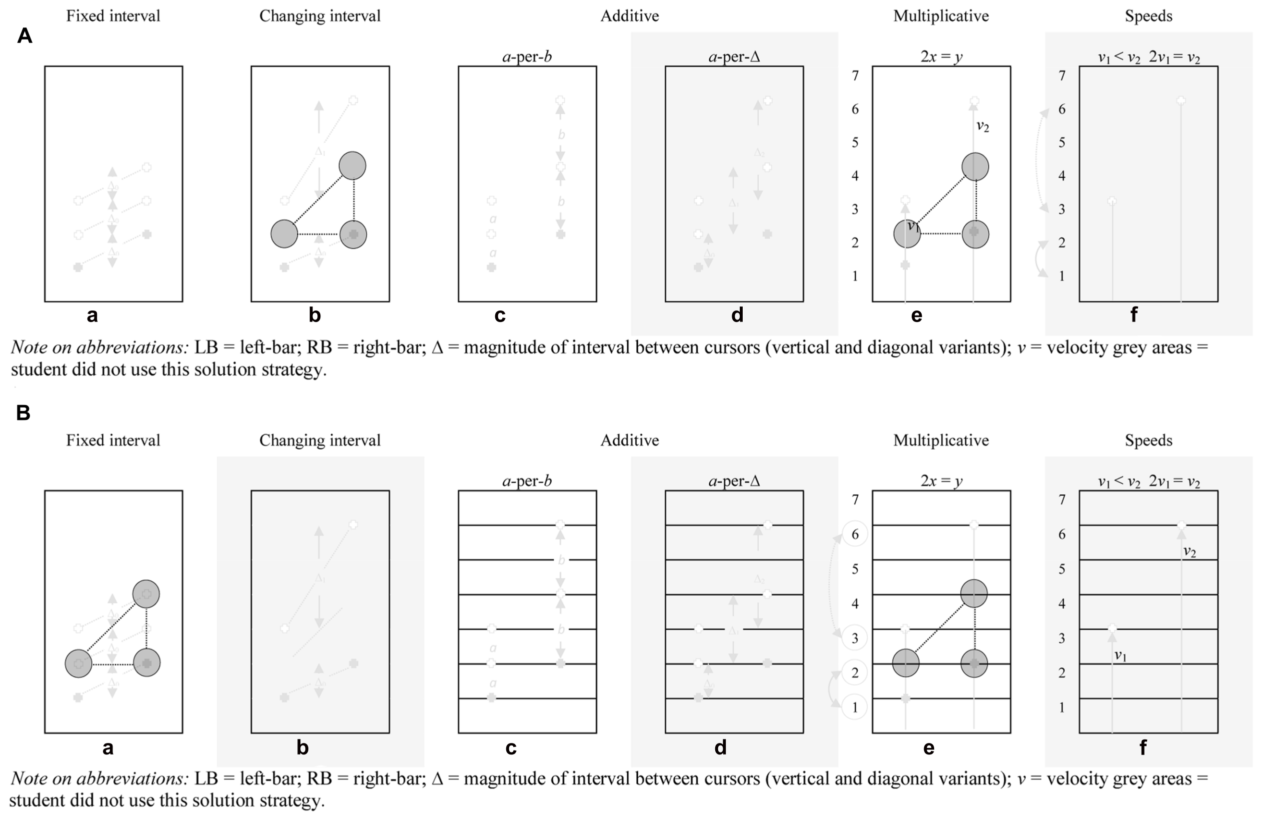


FIGURE 7 | (A) (Student 1) Student generated solution strategies for the make-the-bars-green problem (pre-set proportion 1:2): **(b)** First AA occurred during the changing interval solution strategy (time: 00:58) **(e)** Stating the rule – *blank screen* (time: 06:06), **(d,f)** the solution strategies *a*-per-Δ and speeds were not (yet) mentioned by the student. LB, left-bar; RB, right-bar; Δ = magnitude of interval between cursors (vertical and diagonal variants); *v*, velocity gray areas = student did not use this solution strategy. **(B)** (Student 2) Student generated solution strategies for the make-the-bars-green problem (pre-set proportion 1:2): **(b)** First AA occurred during the fixed interval solution strategy (time: 01:52) **(e)** Stating the rule – *grid supplemented with numbers* (time: 13:25), **(b,d,f)** the solution strategies changing interval, *a*-per-Δ and speeds were not (yet) mentioned by the student.LB, left-bar; RB, right-bar; Δ = magnitude of interval between cursors (vertical and diagonal variants); *v*, velocity gray areas = student did not use this solution strategy.

R: "So, can you explain that?"
S1: "Well, like, that part is just added [*student focuses on the LB*]. For example, this piece [*difference between LB and RB*], actually is doubling the other one [*LB*], so this one [*LB*] is being doubled [*gaze forms a gaze triangle*]."

For his entire solution strategy sequence, see **Figure 8A**. **Figure 7B** shows the developmental trajectory of another student during the critical phase. In general, it took this student longer to state the multiplicative rule than Student 1. This is reflected in the task-phases. Student 1 stated the rule during the first task phase (blank screen), while Student 2 *needed* the symbolic artifacts, not only as a means to enhance, deepen or explain his (naïve) solution procedures, but also to articulate the multiplicative propositions as to why the bars turn green (Abrahamson et al., 2011). In general, Student 2, see **Figure 7B**, had a hard time finding the rule. He articulated many ideas starting with the articulation of some pre-additive rules, the small 'baby steps' toward proportional understanding (Reinholz et al., 2010). Subsequently he conveys the *a*-per-*b* solution strategy. From the *a*-per-*b* solution strategy he *slowly* progresses into a multiplicative framework, as shown in the following excerpt, see **Figure 7B**.

R: "What exactly are you doing?"
S2: "I am following the lines."
R: "Can you explain?"
S2: "[*student's gaze shifts between the top of both bars*] If this one moves up two, this one moves up one [*still the student shifts his gaze between the top of both bars*]."
[...]
R: "And what are you doing right now?"
S2: "I am sort of, following the lines."
R: "Can you explain?"
S2: "Yes, whenever. . .it is starting to double [*intensive gaze shifts between the top of both bars*]."
R: "Ok."
S2: "Because when this one is at 5 [*looking at the numerals*], I have to move that one [*shifting his gaze between numerals and top of the RB*] to 10 [*here the student uses his thumb to show how the LB is half the RB, adding to his perceptual gaze triangle*]."

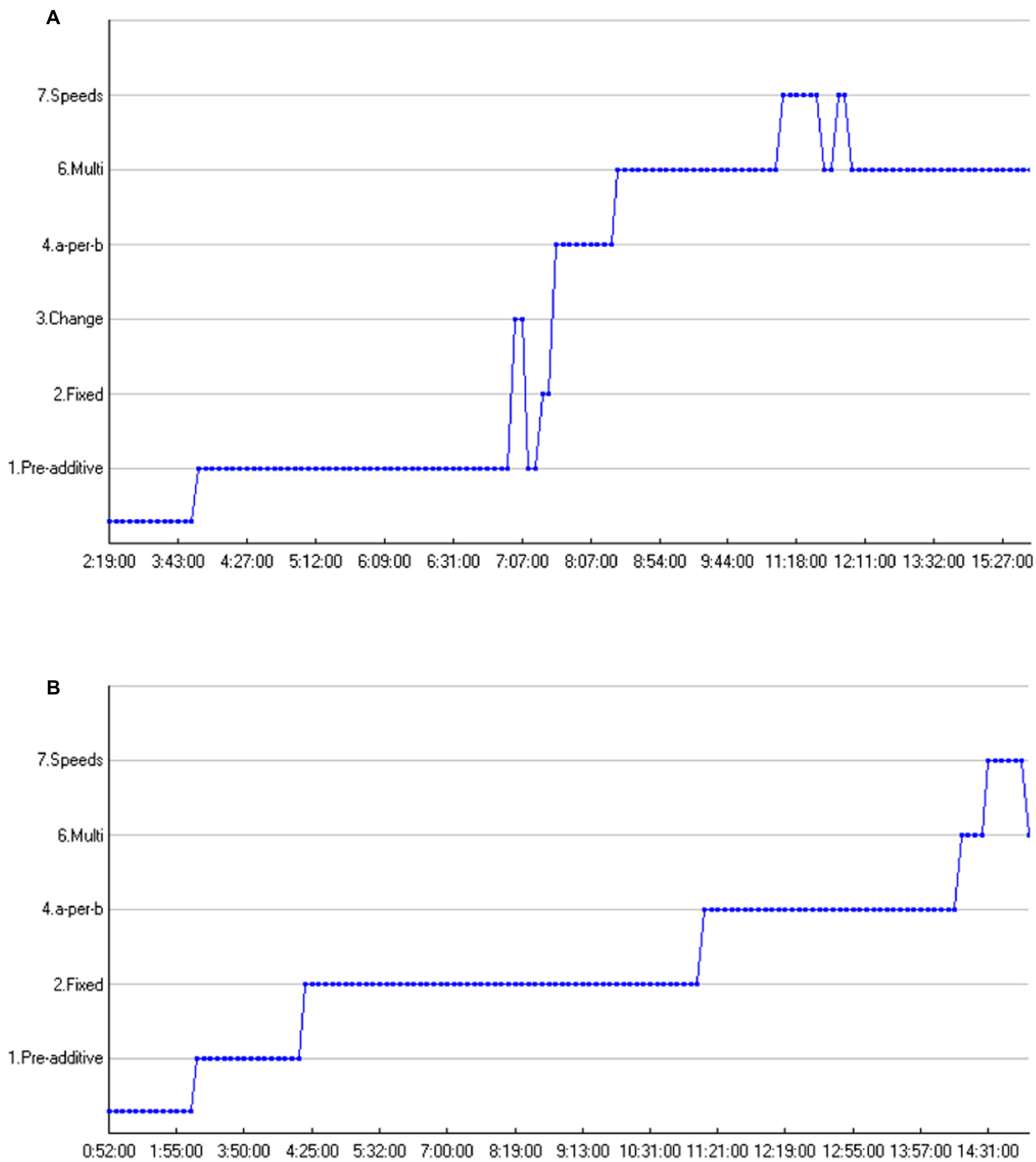


FIGURE 8 | (A,B) Sequences of solution strategies, time path on the *x*-axis. **(A)** Student 1 – Solution strategy sequence. **(B)** Student 2 – Solution strategy sequence.

In this respect, several minutes have gone by between articulating the *a*-per-*b* solution strategy and articulating the first multiplicative strategy. During these moments he tries to reconcile the grid and the grid supplemented with numbers, interpolated onto the problem space, with his existing strategies, and as such largely shows a similar trajectory as the first student, even though the problem *situation* in which they draw their conclusions is rather dissimilar (i.e., blank screen vs. grid supplemented with numbers). Moreover, with respect to perceptual-sensorimotor coupling, for the second student, while he focuses on the top of both bars extensively, he uses his thumb to assist him in making the gaze triangle, and then states the rule. For his entire solution strategy sequence, see **Figure 8B**.

When looking at the solution strategy sequences of both students, some differences and similarities come to the fore, see **Figures 8A,B**. First thing to stress is that a higher point in the graph does not necessarily mean *better*, as was already discussed in the previous section. However, these graphs do give insight in students' transitions toward more correct solution strategies, bearing greater mathematical sophistication, and transitions from additive toward multiplicative solution strategies. The first aspect that comes to the fore is that both students mention a speeds solution strategy after a multiplicative solution strategy. Second, both sequences show how the students transition from additive toward multiplicative solution strategies. In this respect, Student 1 and Student 2 show long periods of additive *a*-per-*b* additive reasoning before progressing toward multiplicative reasoning. Certain transitions are illustrative for the entire sample as was showed quantitatively in the previous section. Another important finding (though not visible in the graphs of these two particular students) is that many students "regressed" to lower solution strategies after having first stated a multiplicative strategy. In this respect, *students were prone to explain their initial multiplicative insights in additive terms before progressing toward multiplicative reasoning*.

Integrative Summary of the Findings

Qualitative and quantitative analysis of the video and eye-gaze data corpus revealed the following patterns:

(1) All students gazed at areas on the screen where there were no particular distinguishing perceptual stimuli *per se*, such as half way along a vertical bar. Believing that these gaze behaviors served the students in better enacting the task's goal motor-actions, we call these patterns "AAs."
(2) Whereas individual students invented AAs spontaneously, similar and even identical AAs recurred across the students.
(3) The AAs are related thematically to the mathematical notions instantiated into the activity (top of the bars and halfway along the tall bar can be considered mathematically relevant areas in the touchscreen task).
(4) Within AAs, some Areas of Interest (AoIs) drew greater gaze frequency and durations (see in **Figure 4**).
(5) Comparison across gaze patterns consisting of two AoIs and three AoIs revealed that the most frequent AoI pair was ambiguous with respect to solution insight but the most frequent AoI triad was unambiguous with respect to solution insight.
(6) Students each deployed a variety of solutions strategies.
(7) Transitions between solution strategies were non-random, with strategies that were more correct or bearing greater mathematical sophistication typically occurring after rather than before strategies that were less correct or bearing lesser mathematical sophistication. In particular, solutions tended to progress from additive toward multiplicative rather than vice versa. This would indicate that the touchscreen tablet application for proportions is a means by which students can progress through proportional stages essential for their development of proportional reasoning.
(8) Fine-grained analysis of data from two students revealed the emergence of a multiplicative gaze pattern followed by improved bimanual motor action and then verbal articulation of a successful solution strategy.

All in all, the results demonstrated that participant students' action, perception, and conceptual understanding developed hand-in-hand through purposeful interaction with a touchscreen tablet application.

DISCUSSION AND CONCLUSION

The aim of the current study was to understand the micro-process by which embodied interaction with a touchscreen application for proportion may lead to mathematical reasoning. Analysis of the eye-tracking and video data implicated the role of AAs in mediating the coordination of action and perception toward more advanced solution strategies. Two research questions framed the data analyses:

(1) What quantitative evidence is there for the emergence of AAs in terms of fixation count, fixation duration, and scan paths?
(2) How does the transition from additive to multiplicative reasoning take place when solving embodied proportions tasks?

The Emergence of Attentional Anchors: Inferences from Quantitative Data

The first question was answered by quantifying the eye-gaze patterns that occurred when students interacted with the touchscreen tablet application for proportions (MIT-Ext). These eye-gaze patterns were contemporaneous with first enactments of effective manipulation and prior to verbal articulations of solution strategies. Analyzing these eye-gaze patterns resulted in quantitative evidence of recurrent gaze patterns to screen locations bearing non-salient stimuli or no stimuli at all yet bearing invariant geometric relations to salient dynamical features. As such these eye-gaze patterns apparently guided the students throughout the problem-solving and reflection process. In particular, the AAs are instrumental in passage from task-inappropriate mathematical reasoning (incorrect additive solution) to task-appropriate mathematical reasoning (correct multiplicative solution).

Transitioning from Additive to Multiplicative Reasoning: The Role of Interaction

It was found that students more often showed a transition from incorrect to correct solution strategies, that is, from additive to multiplicative solution strategies, than vice versa. This indicates that students showed progression toward qualitatively more advanced proportional reasoning at the end of the task than at the beginning of the task. This advancement in reasoning coincided with better coordinated sensorimotor manipulations of the two bars. Case studies illustrated how the emergence of AAs and improved solution strategies co-developed. The dynamics of action-perception-reasoning observed in the current sample speaks for a coherent goal oriented progress in which students use the limited resources available in their working environment to acquire more abstract knowledge in a progressive manner. The path that takes them to reach the goal and to find the 'rule' is unique to their experience, yet it shares the necessary building blocks (such as common solution strategies, gaze patterns, etc.) for proportional learning.

These results have several implications, theoretical as well as educational. First, we have presented one example of design-based research in the domain of mathematics education. In addition to the findings outlined here are the possibilities that embodied-design touchscreen applications offer to the education research in general. The current design together with the multi-modal investigating methodology has shed light on the problem at hand (proportional reasoning) from so many different angles that would have remained in the dark otherwise. Without using touchscreen designs it is not possible to study the role of AAs in bimanual coordination. Without the recording of eye-tracking and thinking-aloud to capture students' perceptual attention and proportional reasoning we would not have found out about the existence of AAs and their correlation with conceptual proportional reasoning. As such, the current study is unique in the sense that it simultaneously studied action, perception, and reasoning and, in doing so, showed how the AA serves as a cognitive pivot in students' transitions from informal goal-directed motions to more formal reasoning about a mathematical idea. In this respect, the construction of AAs preceded the participants' articulation of effective manipulation strategies using mathematical terminology. We thus offer first-ever, triangulating empirical evidence in support of claims for the efficacy of the MIT-tablet application. Moreover, based on this study we can be more specific about what aspects of an educational learning environment are crucial for a student's conceptual development and transfer of knowledge to the task at hand.

Second, given the problems reported about students' and adults' proportional reasoning, in particular the persistence of reasoning additively rather than multiplicatively (Lamon, 2007), we find it promising that so many students move from additive to more advanced multiplicative solution strategies in a brief interview session. Within a relatively short period of time the touchscreen tablet application gives students the opportunity to struggle with the core conceptual challenge of proportion, namely that the arithmetic relations among the quantities in a proportional relation are multiplicative instead of additive and that, therefore, the measured differences among corresponding quantities are unequal. As such, the findings of this study support previous research on proportional reasoning. Since it is generally agreed upon that students move from additive to multiplicative reasoning when learning about proportions, we showed that when using an embodied touchscreen application students follow the same developmental course. In general, students in our sample showed additive reasoning and by means of the application changed this to multiplicative reasoning.

Limitations and Future Directions

The current study did not take differences in verbal ability into account. Since the analyses used largely rely on students' reasoning utterances, it could be that the verbally weak students are at a disadvantage. In the current study we tried to overcome this problem by (1) taking into account the time students spent on the task, and (2) by not looking into total amounts of utterances students had, but at the transitions between utterances. In this respect, verbally weak students are not necessarily at a disadvantage since we assume that every *new* insight is being articulated (i.e., by means of the instruction strategy that we used consistently within tasks and between students). Nevertheless, future research could incorporate a measure of verbal ability and use it as a covariate to control for any differences between students. Another limitation of the current study is that we only looked at the 1:2 proportion. One could argue that this is a special kind of proportion in the sense that multiplication and division are easily applied to it, and its properties can be more easily visualized than say 2:3. As such, students' progress through this interactive learning environment may be specific to tasks of finding simple proportions such as 1:2, and to the affordances of this specific touchscreen application. Therefore, transferability of coordination schemes to other proportions needs to be investigated.

Furthermore, it would be valuable to investigate how the occurrence of action-perception schemes relates to other visualizations of the same mathematical domains, or other mathematical domains. In this study we used vertical bars, but we also intend to investigate how students solve tasks when the objects they manipulate are two sides of a two-dimensional shape such as a rectangle. It can be expected that new challenges will emerge, because proportion would then be situated in a multi-directional context, including horizontal as well as vertical movements. As such, work is done on tasks with orthogonal bars looking into the question how strategies students use differ between parallel and orthogonal versions of the task(s). We expect particular pedagogical pay-offs of different representations and mathematical subdomains. Offering students a variation of tasks in which a certain part of that task is being held constant (i.e., the pre-set proportion), can be a powerful source for learning (Runesson, 2006). We also recommend studying pairs of students interacting on the same task. In this way, students are encouraged to communicate about what they are doing (Abrahamson et al., 2011). In this way, re-description (Karmiloff-Smith, 1995) can be promoted and studied. Preliminary results of this line of research are discussed by Abrahamson et al. (2016).

Another important recommendation for future research is to work with the current tasks in more realistic educational settings. Since the touchscreen application is not designed to solely teach about proportions, it is important to design tasks that can support the properties of the application. Also, students worked on the task for a relatively short period of time. How would action and perception evolve when students have more time to work with the touchscreen application? We also recommend to broaden the scope of what is to be learned. The current study focuses on research in the domain of proportional learning. Further research is also recommended on other topics, also beyond mathematics education (e.g., Nemirovsky et al., 1998; Ferrara, 2014). Last, it seems plausible that sub-populations of students benefit more from embodied design than others. It seems worthwhile to study if students with learning disabilities or problems with symbolic language may gain from embodied experiences.

CONCLUSION

The discovery of attentional anchors underlying students' bimanual coordination bears important implications for the design of educational technology. In particular, our refined instrumentation for tracking and visualizing these phenomenological chimera now enables us to reverse-engineer interaction learning. We begin from a mathematical object we wish students to develop, then we construe this object as constituting an AA for some bimanual task, and finally we implicate this task task's motor-action goals. In a sense, understanding AAs allow educational designers to undo the enactivist evolution from action to perception to cognitive structures, in the service of mathematics learning.

The interview protocol, which was prepared as a research instrument for this study, predicates the experimenter's clinical interventions at various points along the facilitated activity on the participant manifesting target behavioral criteria. One of these behavior–intervention associations is of particular interest to our research, namely our project to understand micro-processes in guided sensorimotor mathematical inquiry with touchscreen tablet applications. This behavior criterion is students' effective enactment of a target dynamical motor-action coordination, namely they are moving their hands all the while keeping invariant certain quantitative relations marked by the hands' momentary locations. As our empirical data demonstrate, although these motor actions manifest multiplicative relations, such as 1:2 ratio, when prompted to articulate their operational strategy the students nevertheless resort to additive structuration. That is, although the dynamical gestalt objectively instantiates an intensive quantity, students explicate their actions in terms of its constituent extensive quantities (specified increments along spatial extensions, such as unitized intervals).

We propose to conceptualize students' behaviors not as unfortunate regressions but as fortunate opportunities. To begin with, we are assuming that sensorimotor coordinations can emerge as solutions to interaction problems before these coordinations can be articulated logically or modeled mathematically. In a sense, one could argue that the mainstay of our naturalistic and cultural manual skills, such as walking, throwing a stone, or using basic kitchen utensils, come about with little to no conscious, structured reflection let alone discourse. Moreover, we perceive the Mathematical Imagery Trainer activities as creating conditions for students to reflect in retrospect on solutions they have already demonstrated in action. We thus reaffirm our earlier implication of the body as the vanguard of mathematical reasoning (Abrahamson, 2014, 2015): We submit that embodied solutions to coordination problems can exhibit quantitative relations that exceed the individual's current mathematical knowledge. We further submit that educational technology for sensorimotor mathematical grounding should therefore create conditions for students to enact dynamical instantiations of concepts at the cusp of their conceptual grasp. The teacher's role is to optimize students' opportunities for conceptual grounding by challenging and supporting them to explicate their manifest behaviors mathematically. By asking them to coordinate complementary visualizations of their own actions, students may ground multiplicative dynamics in additive conceptions (Abrahamson et al., 2014).

These are early days in our line of investigation. Whereas we hesitate to make causal claims regarding the role of AAs in successful learning with tablet applications, the strong correlations among perception, action, performance, and utterance surely point to promising lines of research, which will hopefully result in creating heuristic design frameworks for educational applications within the field of mathematics. Such frameworks could be informed by 'embodied design' (Abrahamson, 2014). In particular, industry informed by embodied design would seek to build touchscreen tablet applications that create opportunities for students to solve motor-action problems designed specifically so as to give rise to targeted proto-conceptual AAs that in turn can assist in reflective abstraction. In our experience the study of what are productive movements and useful coordination schemes in solving tasks that assist in mathematical reasoning is by no means trivial. But with due care, research in this area could inform the work of touchscreen developers building interactive educational applications. In short, touchscreen applications have the potential to be meeting places for action, perception, and cognition.

ETHICS STATEMENT

This study was approved by the ethical committee board of the faculty of Social Sciences at Utrecht University. Informed consent was obtained from the legal guardians of all students involved.

AUTHOR CONTRIBUTIONS

All authors contributed extensively to the work presented in this paper. CD and SS took the lead in data gathering and data analysis. All authors were involved in the conception and design of the work; all authors significantly contributed in drafting and revising the work; all authors approve of the version to be published and all authors are accountable for all aspects of the work in ensuring that questions related to the accuracy or integrity of any part of the work are appropriately investigated and resolved.

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Conflict of Interest Statement: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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ORIGINAL RESEARCH
published: 25 January 2017
doi: 10.3389/fpsyg.2017.00055

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Do Young Chinese Children Gain Anthropomorphism after Exposure to Personified Touch-Screen and Board Games?

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Research shows that preschoolers are likely to anthropomorphize not only animals, but also inanimate toy after being exposed to books that personify these objects. Can such an effect also arise through young children's use of touch-screen games? The present study is the first to examine whether playing a touch-screen personified train game affects young children's anthropomorphism of real trains. Seventy-nine 4- and 6-year-old children were randomly assigned to play either a touch-screen game or a board game of Thomas the Tank Engine for 10 min. They completed the Individual Differences in Anthropomorphism Questionnaire–Child Form (IDAQ-CF) (two subscales: Technology/Inanimate Nature, Animate Nature) and an additional four items about the anthropomorphism of real trains, before (T1) and after (T2) the game. Overall results showed that children manifested a small but statistically significant increase in anthropomorphizing of real trains after their exposure to both games, claiming that real trains were like humans. Interestingly, 4-year-old children in the board game group tended to anthropomorphize real trains more than those in the touch-screen group, whereas the reverse was true for the 6-year-old children. The results suggest that touch-screen games may delay the decline of children's anthropomorphism during the cognitive and socio-emotional transition that occurs in children aged 5–7. These findings have implications for future research on how touch-screen games increase children's anthropomorphism of the real world, and more generally, for evaluation of the influence of the growing use of touch-screen games on young children's learning.

Keywords: touch screen, game, transfer, children, anthropomorphism

OPEN ACCESS

Edited by:
Gabrielle Strouse, University of South Dakota, USA

Reviewed by:
Steven Stagg, Anglia Ruskin University, UK
Angela Nyhout, University of Toronto, Canada
Megan Geerdts, William Paterson University, USA

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Specialty section:
This article was submitted to Developmental Psychology, a section of the journal Frontiers in Psychology

Received: *31 May 2016*
Accepted: *10 January 2017*
Published: *25 January 2017*

Citation:
Li H, Hsueh Y, Wang F, Bai X, Liu T and Zhou L (2017) Do Young Chinese Children Gain Anthropomorphism after Exposure to Personified Touch-Screen and Board Games? Front. Psychol. 8:55. doi: 10.3389/fpsyg.2017.00055

INTRODUCTION

Recent survey data suggest that young children start to use tablets at a very early age, most often to watch videos and play video games (Common Sense Media, 2013). This playful use of various media affects their development and learning (Moreno, 2016). A great amount of anthropomorphism exists in interactive games designed for young children, with inanimate objects and animals being made to look and act like humans (for a review, see Hartman and Vorderer, 2009), a phenomenon already widely observed in children's picture books about animals and their natural environment (Marriott, 2002).

In recent years, touch-screen devices have become prevalent in children's lives (Cristia and Seidl, 2015), being more interactive than earlier play media such as picture books and board games. In this area of research, three features of touch-screen devices stand out: interactivity, tailorability, and progression (Christakis, 2014). The salient feature of interactivity of touch screens allows children not only to anthropomorphize the character in a game, but also to get reactions by touching it. Such multimodal stimulation creates a sense of presence (Preston, 2007) in which the user feels as though he or she were physically present in the scene (Benski and Fisher, 2013).

But recent research in spatial cognition points to another critical feature of the touch screen: it is 2-dimensional (2D). Young children's understandings of 2-dimensional representations improve significantly between 5 and 6 (Frick and Newcombe, 2015; Lytle et al., 2015). Studies showed that although 5-year-olds performed well on a task involving a 2D image rotating on a touch-screen, 4-year-olds performed only at chance (Frick et al., 2013a,b). In other words, children older than 5 become able to understand and manipulate 2D representations.

Then, does young children's exposure to a personified object in 2D touch-screen games or 3D board games affect their anthropomorphic understanding of the world? One recent study suggested that preschoolers' exposure to an anthropomorphic storybook increased the likelihood that they would view real trains as possessing human qualities (Li et al., 2015). Could the effect of anthropomorphism found in storybooks also exist in children's exposure to touch-screen games? As touch-screen devices become increasingly accessible to young children, their impact on children's anthropomorphism raises important but under-researched questions about young children's thinking and behavior. We designed two similar games, one board game and one touch-screen game, with an anthropomorphic character, Thomas the Tank Engine, to investigate the effects of playing each game on young children's anthropomorphism of trains in the real world. Thomas was chosen for this study because it is a popular personified train character, and it is easy for preschoolers to relate to a real train.

Anthropomorphism has been defined as attributing uniquely human characteristics to non-human agents or events, like animals and vehicles (Waytz et al., 2010). Anthropology and psychology have seen a long-lasting interest in anthropomorphism and the related concept of animism (e.g., Tylor, 1871; McDougall, 1911; Piaget, 1929; Looft and Bartz, 1969; Epley et al., 2007). Previous research has shown that 4- and 5-year-old urban children describe their biological knowledge of animals in an anthropocentric way (Springer and Keil, 1989; Waxman and Medin, 2007). Some argue that the anthropomorphism of animals can hinder children's understanding of the biological world (Ganea et al., 2011, 2014; Legare et al., 2013). Like animism, which declines with age (Jahoda, 1958; Inagaki, 1989), anthropomorphism declines noticeably from early to middle childhood (Severson and Lemm, 2016) following the so-called period of "the age of reason" (White, 1996).

We designed the present study to assess the effect of a touch-screen game and a board game on 4- and 6-year-old children's anthropomorphism. Each age group was divided into two game groups, namely, board game and touch-screen game. The game was organized around the activities of Thomas the Tank Engine, a personified train. Children's general anthropomorphism and specific anthropomorphism of trains were assessed before the game and 1 day later. Our main question was: Would an animated touch-screen game affect young children's anthropomorphism in a similar way as an animated board game would? For the reasons above, our first hypothesis was that children would show increased anthropomorphism in the touch-screen condition, just as they would in the board game condition. Our second hypothesis was that the older children were, the less they would anthropomorphize real trains.

The focus of this study was on the changes from T1 to T2, and interactions between this change and other factors, rather than a direct comparison between the two types of games. As noted, we expected the pattern of results to be similar across the two types of games. In cases where we did find differences between the two media, we offer tentative interpretations, as we did not make hypotheses about these differences.

MATERIALS AND METHODS

Participants

Seventy-nine children from a kindergarten in central China participated in the study, 39 4-year-olds (16 girls, $M_{age} = 54.97$ months, $SD = 2.62$) and 40 6-year-olds (15 girls, $M_{age} = 73.85$ months, $SD = 1.46$). They were randomly assigned to two groups: board game and touch-screen game. Parents reported that the children first saw a real train between their first and second birthday, both in the touch-screen group ($M_{age} = 15.9$ months, $SD = 13.9$) and in the board group ($M_{age} = 22.7$ months, $SD = 11.1$). The first encounter with Thomas the Tank Engine in different media was similar between the two groups (**Table 1**). There was no significant difference in their usage frequency, nor was there any significant group difference in children's prior knowledge of Thomas the Tank Engine in other media (**Table 2**). Additionally, during the 2 weeks before the study, the two groups did not differ in their exposure to Thomas the Tank Engine either on iPad or in board games.

Parents and teachers provided consent for all the participating children. Each child was given a sticker as a token of appreciation at the end of participation. The present research was approved by the Committee on Ethical Research Practice of the university with which the third author is affiliated.

Measures

Individual Differences in Anthropomorphism Questionnaire-Child Form (IDAQ-CF), a highly reliable measure (12 items, $\alpha = 0.80$) (Severson and Lemm, 2016), was translated into Chinese and then back-translated into English to ensure the original meanings. The original IDAQ-CF contained three subscales: Technological Nature with four items: robot, TV, car, and computer; Inanimate Nature with four items: mountain, ocean, tree, wind; and Animate Nature with four items: cheetah, turtle, insect, and lizard. However, because the Technological

TABLE 1 | Children's age (months) at first encounter with Thomas the Tank Engine in different media.

Types	Storybooks			DVD/Television			Board game			Touch-screen game		
	N	*M*	*SD*	*N*	*M*	*SD*	*N*	*M*	*SD*	*N*	*M*	*SD*
Board	27	27.5	7.40	27	24.0	11.53	23	27.8	11.25	5	41.4	14.76
Touch-screen	28	29.5	11.55	24	28.9	9.99	28	28.1	11.48	6	32.5	12.32

TABLE 2 | Children's basic anthropomorphism at T1 and T2 in 4-year-olds and 6-year-olds.

Age	Group	*N*	T1TIN		T1ANI		T2TIN		T2 ANI	
			M	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*
4	Board	19	1.06	0.88	1.44	0.89	1.25	0.90	1.34	0.88
	Touch-screen	20	0.88	0.71	1.44	0.70	0.92	0.71	1.04	0.61
6	Board	19	0.75	0.76	1.57	0.74	0.91	0.82	1.26	0.74
	Touch-screen	21	0.64	0.57	1.54	0.56	0.69	0.74	1.26	0.58

T1, Time 1; T2, Time 2; TIN, Technology/Inanimate-Nature; ANI, Animate Nature.

and Inanimate Nature items loaded well onto the same factor (Severson and Lemm, 2016), they were combined in our analyses, resulting in two subscales: Technology/Inanimate-Nature (mean score for items 1–8), and Animate Nature (mean score for items 9–12). The same 12-item Chinese version of IDAQ-CF was used to measure the level of anthropomorphism at Times 1 and 2.

Each item had two questions for the child to answer. First, for example, does a TV have feelings, like happy and sad? If the child said no or gave no response, the child completed the item with a score of 0. If yes, the child was asked the second question, how much? On completing the second question, the child received a score between 1 and 3 to indicate a little, or a medium amount, or a lot. An average score across all items fell within the range of 0–3. This scoring method also applied to four new questions added to measure the anthropomorphism of real trains as follows.

Q13. Does a real train have feelings, like being happy and sad? If yes, how much feeling does a real train have?
Q14. Does a real train know what it is? If yes, how much does a real train know what it is?
Q15. Does a real train do things on purpose? If yes, how much does a real train do things on purpose?
Q16. Does a real train think for itself? If yes, how much does a real train think for itself?

At both T1 and T2, all 16 items were presented randomly. Before the 16 items were presented at T1and T2, three pairs of training questions from the IDAQ-CF were administered to ensure that children understood the type of questions that would be asked and how to respond to them. For example, "Do you like candy (broccoli, carrots)? If yes, how much?" The same scoring system was used as for the above 16 items. The scores of training questions were not included in the data analysis because they were only used for children's familiarity with the scale.

Each child's play session was video recorded to examine how engaged each child was in playing. Later, the video time code was used in the unit of seconds to mark the durations of the child's eyes-on-the-game behaviors and the child's eyes-off-the-game behaviors. The ratio of the total duration of eyes-on-the-game (attention) to the total time of playing was used as an index of the child's play engagement. One rater coded all the videos during children's play. The other rater coded 10 randomly selected videos (five from each condition). The inter-rater reliability for the index of attention was $r = 0.997$, $p < 0.01$ and for the index of distraction, $r = 0.937$, $p < 0.01$.

A parent questionnaire was used to assess the children's first encounter and life experience with real trains, and how often the children were exposed to the board game and touch-screen game of Thomas the Tank Engine during the 2 weeks before the study. No differences were found between age groups or between the two game groups in terms of previous game experience, first encounter or real experience with real trains or Thomas the Tank Engine (ps > 0.05).

Materials and Procedure

Both games focused on playing with the personified characteristics of Thomas the Tank Engine. The children were asked to help Thomas transport people and cargo to prepare for a birthday party by moving (board game) or touching (touch-screen game on iPad) Thomas. The two games were designed to be similar to each other, using Thomas the Tank Engine as the personified character and having it follow a similar routine. Both groups were asked to add a cave over the railroad and plant a tree by the railroad. They also needed to transport goods represented by stickers including the following images: orange, papaya, pear, cherry, and lemon, a bunch of balloons, a group of seven children, Santa Claus with a gift box.

The study went on for 2 days. On Day 1, every child completed the pre-test using the IDAQ-CF. On Day 2, they played the assigned game for 10 min and completed the post-test. One experimenter administered the play session, but another conducted both pre- and post-test in order to avoid the experimenter effect. Before playing the game, the child was told, "You will play a game to help Thomas transport cargo and people today. Look! This is our friend Thomas. He is very nice, and willing to help others. He knows he is a train, and he often helps his friends. There will be a birthday party today. Can you help Thomas finish the task?" Then the experimenter showed the child where to start and to end on the railroad, and how to move the train. The child was also asked to put the tree and the cave along the railroad. After the experimenter verified the child's understanding of the game, the child began playing independently, sometimes with encouragement.

RESULTS

Basic Anthropomorphic Effects

A 2 (age) × 2 (condition) × 2 (time) mixed-effects ANOVA was conducted, with age (4, 6) and condition (board game, touch-screen game) as between-subjects factors and time (T1, T2) as a within-subjects factor. The two dependent variables were the two key score categories of the IDAQ-CF: Technology/Inanimate-Nature, Animate-Nature.

For the Technology/Inanimate-Nature score, there was a main effect of time: the children showed marginally higher anthropomorphic scores at T2 ($M = 0.94$, $SE = 0.09$) than at T1 ($M = 0.83$, $SE = 0.08$), $F(1,75) = 4.00$, $p = 0.049$, $\eta_p^2 = 0.05$. The main effect of age [$F(1,75) = 2.91$, $p = 0.09$, $\eta_p^2 = 0.04$] and condition [$F(1,75) = 0.83$, $p = 0.36$, $\eta_p^2 = 0.01$], and the interactions of time and condition [$F(1,75) = 0.83$, $p = 0.37$, $\eta_p^2 = 0.01$], time and age [$F(1,75) = 0.01$, $p = 0.92$, $\eta_p^2 < 0.001$], and condition and age [$F(1,75) = 0.12$, $p = 0.73$, $\eta_p^2 = 0.002$], as well as the three-way interaction of age and condition and time [$F(1,75) = 0.02$, $p = 0.90$, $\eta_p^2 < 0.001$] were all non-significant.

For the Animate-Nature score, there was also a main effect of time: however, contrary to expectations, the children showed significantly lower anthropomorphic scores at T2 ($M = 1.22$, $SE = 0.08$) than at T1 ($M = 1.42$, $SE = 0.08$), $F(1,75) = 9.44$, $p = 0.003$, $\eta_p^2 = 0.11$. The main effect of age [$F(1,75) = 1.50$, $p = 0.22$, $\eta_p^2 = 0.020$] and condition [$F(1,75) = 0.95$, $p = 0.33$, $\eta_p^2 = 0.013$], and the interaction of time and condition [$F(1,75) = 0.01$, $p = 0.94$, $\eta_p^2 < 0.001$], time and age [$F(1,75) = 2.75$, $p = 0.10$, $\eta_p^2 = 0.035$], and condition and age [$F(1,75) = 0.31$, $p = 0.58$, $\eta_p^2 = 0.004$], as well as the three-way interaction of age and condition and time [$F(1,75) = 0.01$, $p = 0.91$, $\eta_p^2 < 0.001$] were all non-significant.

Anthropomorphic Scores for Real Trains

A 2 (age) × 2 (condition) × 2 (time) mixed-effects ANOVA was conducted to compare the anthropomorphic scores for real trains, with age (4, 6) and condition (board game, touch-screen game) as between-subjects factors and time (T1, T2) as a within-subjects factor. The dependent variable was the score for anthropomorphism about trains. Results showed that the main effect of time was significant [$F(1,75) = 5.54$, $p = 0.02$, $\eta_p^2 = 0.069$], in that the anthropomorphic scores on pretest ($M = 0.90$, $SE = 0.09$) were lower than those on post-test ($M = 1.05$, $SE = 0.11$). Also, the main effect of age was significant, $F(1,75) = 4.99$, $p = 0.03$, $\eta_p^2 = 0.062$, in that 4-year-old children had higher scores ($M = 1.19$, $SE = 0.14$) than 6-year-old children ($M = 0.75$, $SE = 0.14$).

The three two-way interactions, namely time and age [$F(1,75) = 0.10$, $p = 0.76$, $\eta_p^2 = 0.001$], time and condition [$F(1,75) = 0.16$, $p = 0.69$, $\eta_p^2 = 0.002$], and age and condition [$F(1,75) = 0.003$, $p = 0.96$, $\eta_p^2 < 0.001$] were non-significant. Interestingly, however, there was a trend for a three-way interaction among age, condition, and time, [$F(1,75) = 3.37$, $p = 0.07$, $\eta_p^2 = 0.04$]. A simple effects analysis revealed that the 4-year-olds in the board game condition anthropomorphized real trains in T2 ($M = 1.41$, $SE = 0.22$) more than T1 ($M = 1.15$, $SE = 0.19$) [$F(1,75) = 4.24$, $p = 0.04$, $\eta_p^2 = 0.054$]. However, the 6-year-olds in the touch-screen condition anthropomorphized real trains in T2 ($M = 0.81$, $SE = 0.22$) more than T1 ($M = 0.54$, $SE = 0.19$) [$F(1,75) = 4.66$, $p = 0.03$, $\eta_p^2 = 0.058$] (**Figure 1**). In short, at T2, 4-year-old children in the board game condition gained more anthropomorphism of real trains whereas 6-year-old children did so in the touch-screen condition.

Children's Attention during Play

In order to understand how children's engagement during play might affect the results, two raters coded the time of attention (i.e., total time attending divided by total play time) and the time of distraction (i.e., total time distracted divided by total play time) separately to create the indexes of attention and distraction, using the time code on the video. After setting aside two outliers which were three standard deviations above or below the children's mean time of attention, a 2 (age) × 2 (condition) MANOVA was conducted to test whether there were differences in the ratio of attention and distraction.

Results showed main effects of age [Wilk's $\Lambda = 0.941$, $F(1,73) = 4.57$, $p = 0.036$, $\eta_p^2 = 0.059$] and condition [Wilk's $\Lambda = 0.945$, $F(1,73) = 4.27$, $p = 0.042$, $\eta_p^2 = 0.055$]. Follow-up analyses showed that there were significant age differences in the ratio of attention, in that 6-year-old children ($M = 0.99$, $SE = 0.004$) had higher attention ratio than 4-year-old children ($M = 0.97$, $SE = 0.006$), $F(1,73) = 4.57$, $p = 0.036$, $\eta_p^2 = 0.059$; however, 4-year-old children ($M = 0.03$, $SE = 0.06$) had a higher ratio of distraction than 6-year-old children ($M = 0.01$, $SE = 0.004$), $F(1,73) = 4.57$, $p = 0.036$, $\eta_p^2 = 0.059$. There were also condition differences in the ratio of attention, in that children in the touch-screen game condition had a higher attention ratio ($M = 0.99$, $SE = 0.002$) than those in the board game condition ($M = 0.97$, $SE = 0.006$), $F(1,73) = 4.27$, $p = 0.042$, $\eta_p^2 = 0.055$; in contrast, children in the board game condition had a higher distraction ratio ($M = 0.03$, $SE = 0.04$) than those in the touch-screen game condition ($M = 0.01$, $SE = 0.002$), $F(1,73) = 4.27$, $p = 0.042$, $\eta_p^2 = 0.055$.

A series of 2 (age) × 2 (condition) × 2 (time) mixed-effects ANCOVAs, ratio of attention as covariate, IDAQ-CF scores and trains scores as dependent variables, were conducted to test whether ratio of attention influenced the result. Results

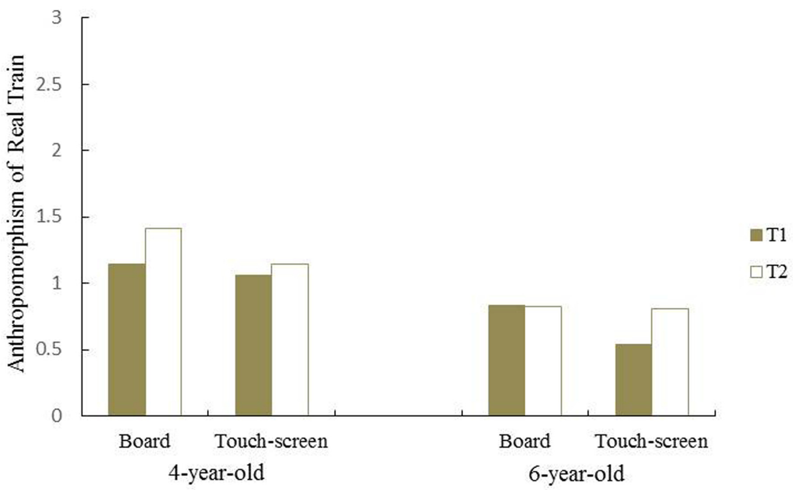

FIGURE 1 | Pre and Post Anthropomorphism of real train at T1 and T2 in 4-year-olds and 6-year-olds.

showed that the effect of the covariate was non-significant, Fs (1,72) < 3.84, $ps > 0.05$.

DISCUSSION

The present study tested whether Chinese young children would show greater anthropomorphism about real trains after being exposed to a board game or a touch-screen game that personified Thomas the Tank Engine. We assessed children's anthropomorphism of real trains before and after playing one of the two games, both of which featured the personified train that has a human face on the front. It is important to note that there was an overall increase in children's anthropomorphism of real trains following either game, which replicates other researchers' findings (e.g., Herrmann et al., 2010; Ganea et al., 2014; Li et al., 2015) and supports the view that young children's exposure to media with strong personified features can increase their anthropomorphism in the real world. The results support our first hypothesis that children would be likely to anthropomorphize real trains after playing either game. However, they only partially support our second hypothesis that the older children were, the less they would anthropomorphize real trains; specifically, the 3D board game data support this hypothesis but the 2D touch screen game data do not.

In our sample, there was a non-significant age difference in children's general anthropomorphism (assessed by the two IDAQ-CF subscales) both before and after the game. Such a non-significant age difference in anthropomorphism of Technology/Inanimate-Nature subscale is consistent with the data the IDAQ designers obtained on the same subscale (Severson and Lemm, 2016). Although they found a significant age difference between 5 and 9 in the Animate-Nature subscale, this subscale was not particularly sensitive to the two younger age groups, 4 and 6. It is not surprising that our finding shows no significant age difference because participants in the present study were even younger.

It is interesting to note that Animate-Nature scores decreased from T1 to T2, in both age groups, but Technology/Inanimate-Nature scores did not. This finding is consistent with a study by Severson and Lemm (2016), who found that children who endorsed anthropomorphism of animals were less likely to ascribe animate characteristics to the robot and that the two IDAQ-CF subscales might have some inverse relationship. One possible interpretation of this result is that children were exposed to animate items only through verbal and visual representations while they were physically and mentally engaged with a personified train in the game. Because children did not have difficulty identifying living things as animate by correlating various cues (Arterberry and Bornstein, 2002; Rakison and Lupyan, 2008), their anthropomorphism of animals might remain stable without the game conditions. In the current study, the game conditions did not direct children's attention to these living things further, but provided more dynamic cues, namely, human-typical acts, for children to process. These dynamic cues involved agency (e.g., making the train do things), intentionality and goal-directedness (e.g., transporting people and planting trees) (for a review, see Opfer and Gelman, 2011). The child's mind processed the immediate cognitive input from the personified acts of Thomas while the mind might leave little room for processing the information from the Animate subscale. A strongly personified Thomas the Tank Engine made the animate less important in the child's mind than before the game, resulting in a small but significant decrease.

However, it should be noted that the two game conditions in the present study highlighted the personified feature of the object, Thomas the Tank Engine, and the interactive feature of the game. These two features were not integral to the IDAQ-CF, which is a verbal measure. Adding the four train items to the IDAQ-CF was driven by our research question about the potential impact of the two game conditions on young children's anthropomorphism of real trains. It becomes clear that this apparent inconsistency above warrants further research to assess the possible difference in young children's anthropomorphism between verbal exposure and physically involved exposure to a medium, including exposure to the realistic train.

There was a trend for an interesting interaction between age group and game type in terms of anthropomorphizing real trains. The 4-year-old group showed more anthropomorphism of real trains after playing the board game, whereas for the 6-year-old group the effect was larger after playing the touch-screen game. As mentioned, there is reason to believe that the age difference in children's anthropomorphism of real trains may be moderated by the game type, especially due to the game dimensionality. Recent research shows that 4-year-olds are able manually and observationally respond to 3D objects correctly, but respond to 2D objects at chance in all conditions. However, there is a developmental watershed between ages 5 and 6. Six-year-olds respond significantly better to the 2D objects (Frick et al., 2013a,b; Frick and Newcombe, 2015; Lytle et al., 2015).

These findings help explain why 4-year-olds showed a higher level of anthropomorphism toward the real trains at T2 than 6-year-olds in the board game group: 3D objects are easier or more meaningful, and therefore, they were more susceptible to the influence of the personified train. In contrast, although 6-year-olds developmentally were less likely to anthropomorphize inanimate objects, the touch-screen game appeared to set back this developmental progress at T2 with the personified 2D object, Thomas the Tank Engine, probably because the 2D image manipulation is an emerging ability. Other researchers note that 6-year-olds's performance on 2D images are far from perfect and even 7-year-olds only reach 79% accuracy (Frick and Newcombe, 2015). By the same logic, we may see that 4-year-olds in the touch screen condition and the 6-year-olds in the board game condition did not show significant change from T1 to T2, but for different reasons.

Sociocultural researchers also show evidence that children at six experience noticeable cognitive and socio-emotional transitions (Rogoff et al., 1975; White, 1996), and their tendency to anthropomorphize actual objects should have decreased unless the media environment, the touch-screen game in this case, interferes with this transition. As newly fashioned cultural tools, touch-screen media with its immediately interactive engagement with 2-dimensional objects may present parents, teachers and psychologists a new set of developmental questions to pursue in both practice and research. It leads us to speculate that personified media in general, including the fast-growing market of tablet game apps, can have similar effects on young children.

This interpretation echoes the concern that science educators of young children have raised. Recall the earlier argument that the anthropomorphized animals in children's literature can hinder children's understanding of the biological world (Gallant, 1981; Legare et al., 2013; Ganea et al., 2014). Some insist that it would be better to depict the world in children's books realistically rather than anthropomorphically (Richert et al., 2009; Ganea et al., 2011). The possible touch-screen-facilitated increase of anthropomorphism in 6-year-old Chinese children may provide the first evidence for science educators to further consider the possible effect of tablets in teaching biological science to young children.

It is interesting to note that 6-year-olds' attention ratio was on average greater than 4-year-olds'. This finding is in line with the observation of attention span in child development. As children grow into middle childhood, they have more deliberate and self-regulated control of attention (Dossett and Burns, 2000). However, what is more interesting is that children's engagement in the touch-screen condition is greater than that in the board game condition. Taking these differences together with the interaction trend reported above, we may ask whether such higher level of engagement with the touch-screen game would be a reason for intensifying 6-year-olds' tendency to anthropomorphize real trains. This is a question for our future research.

The current research used a between-subjects design, a design observable in similar studies in two conditions (touch-screen or electronic toy version and physical toy version) without a control group (e.g., Zosh et al., 2015; Huber et al., 2016) because the focus of the study was on the changes from T1 to T2, and interactions between this change and other factors, rather than a direct comparison between the two types of games. In fact, we expected that children's anthropomorphism would increase from pretest to post-test, following a similar pattern across the two types of games. However, future research can include a control condition to address the effect of different media treatments.

In summary, the present research suggests that Chinese 4- and 6-year-old children can show greater anthropomorphism about a certain object (in this case, a train) by playing personified games involving the object in a certain context. The board game context had a greater effect on 4-year-olds due to its 3-dimensional quality while the touch screen game context affected 6-year-olds paradoxically due to their developmental gain in spatial cognition. Our study offers tentative evidence for understanding a new dimension of anthropomorphism in young children. Media play an important role in representing an anthropomorphic world to children, and touch-screen games might contribute more to 6-year-old children's anthropomorphism than board games. This first attempt to examine the role touch-screen media play in young children's anthropomorphism provides new directions for our future research.

ETHICS STATEMENT

This study was approved by the Institutional Review Board of Central China Normal University. All the parents had signed the consent inform before the study.

AUTHOR CONTRIBUTIONS

HL developed the study concept. All authors contributed to the study design. HL, FW, and LZ performed the experiment, and FW conducted the statistical analyses. HL and YH were primarily responsible for writing the manuscript, with all remaining authors providing critical revisions. All authors approved the final version of the manuscript for submission.

FUNDING

This research was funded by China Postdoctoral Science Foundation Funded Project (No. 2015M580210) and China International Postdoctoral Exchange Fellowship Program (No. 20160054) to the first author HL, National Natural Science Foundation of China (No. 31300864) to FW, National Natural Science Foundation of China (No. 81471629) and Tianjin Science and Technology Planning Project (No.12ZCZDSF07100) to XB, and National Natural Science Foundation of China (No. 61503421) to TL.

ACKNOWLEDGMENT

We wish to thank the children, their parents and teachers for participating in this study.

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Conflict of Interest Statement: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

frontiers in Psychology

ORIGINAL RESEARCH
published: 15 December 2016
doi: 10.3389/fpsyg.2016.01951

Curling Up With a Good E-Book: Mother–Child Shared Story Reading on Screen or Paper Affects Embodied Interaction and Warmth

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This study compared changes in cognitive, affective, and postural aspects of interaction during shared mother and child book reading on screen and on paper. Readers commonly express strong preferences for reading on paper, but several studies have shown marginal, if any, effects of text medium on cognitive outcomes such as recall. Shared reading with a parent is an engaging, affective and embodied experience across time, as well as a cognitive task, so it is important to understand how paper vs. screen affects broader aspects of these shared experiences. Mid-childhood sees a steep rise in screen use alongside a shift from shared to independent reading. We assessed how the medium of paper or screen might alter children's shared reading experiences at this transitional age. Twenty-four 7- to 9-year-old children and their mothers were videotaped sharing a story book for 8 min in each of four conditions: mother or child as reader, paper, or tablet screen as medium. We rated videotapes for interaction warmth and child engagement by minute and analyzed dyadic postural synchrony, mothers' commentaries and quality of children's recall, also interviewing participants about their experiences of reading and technology. We found no differences in recall quality but interaction warmth was lower for screen than for paper, and dropped over time, notably when children read on screen. Interactions also differed between mother-led and child-led reading. We propose that mother – child posture for paper reading supported more shared activity and argue that cultural affordances of screens, together with physical differences between devices, support different behaviors that affect shared engagement, with implications for the design and use of digital technology at home and at school. We advocate studying embodied and affective aspects of shared reading to understand the overall implications of screens in children's transition to independent reading.

Keywords: shared-reading, tablets, embodied cognition, synchrony, affect, human–computer interaction (HCI)

OPEN ACCESS

Edited by:
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Specialty section:
This article was submitted to Developmental Psychology, a section of the journal Frontiers in Psychology

Received: *30 September 2016*
Accepted: *29 November 2016*
Published: *15 December 2016*

Citation:
Yuill N and Martin AF (2016) Curling Up With a Good E-Book: Mother–Child Shared Story Reading on Screen or Paper Affects Embodied Interaction and Warmth. Front. Psychol. 7:1951. doi: 10.3389/fpsyg.2016.01951

INTRODUCTION

When children share reading with their parents, on the road to becoming independent readers, does it matter whether they share stories using a traditional paper book or a tablet screen? Intense media interest surrounds the question of whether reading on screen differs from reading on paper, and there is now a small but growing literature on the topic. Many adults express a preference for paper (Pew Research Center, 2016) and sales of paper books have recently shown a small rise as e-book sales have slightly declined (Publishers Association, 2015). Where children are concerned, there has been strong concern about the amount of 'screen time', with fears that children reading from screens may not derive the same benefits as those reading from paper, and that digital devices will discourage children from reading for pleasure. In one recent report, 74% of parents said they would rather their child read a print book than an e-book, and 50% of parents of 5- to 7-year-olds worry about their child's excessive use of screens (Egmont, 2013). Conversely, a report from the National Literary Trust suggested that using e-books may increase the motivation and reading skills of young readers, particularly poorer performing boys (Picton and Clark, 2015). These questions have practical importance because parental involvement in reading influences children's later language and literacy development (e.g., Bus et al., 1995; Senechal and LeFevre, 2002) and is entwined with the attachment relationship of parent and child (Bus and van Ijzendoorn, 1995). Shared reading is a potent environment for the sort of positive parent—child interaction that can contribute to socio-emotional development, as well as literacy (Aram and Aviram, 2009).

As technology becomes increasingly pervasive in children's lives, the question of how digital technology affects their literacy and enjoyment of stories becomes more pressing. Figures from the UK communications regulator Ofcom (2015) show that the use of digital technology for entertainment is now something that even the youngest toddler encounters. The use of technology is also widespread in schools, so children's experience of reading, both at home and at school, is increasingly through the medium of a screen.

Research on children's reading from screens has focused, understandably, on young children who are just learning to decode text, and most of these studies therefore involve adult-led shared reading. Children's early experiences of books, whether on paper or on screen, are thus typically triadic interactions – reading device, child and adult. An increasingly influential approach in the field of human—computer interaction (HCI) is that of 'embodied interaction', 'the creation, manipulation, and sharing of meaning through engaged interaction with artifacts' (Dourish, 2004, p. 126), emphasizing the everyday social practices and physical reality through which people interact with technology, involving shared awareness, construction of meaning and emotions. Joint book-reading fundamentally involves the shared construction of meaning between adult and child, with the different opportunities and constraints provided by books or screens, both in terms of their physical properties and their social significance. Studying shared reading with this perspective in mind can help us see the contribution of different aspects of the natural situations in which joint reading happens. Potential differences in cognitive outcomes, such as comprehension, are without doubt important, but research also needs to investigate affective, interactional, and embodied factors that are central to the experience of early shared reading: child engagement in the story, interaction warmth and postural synchrony, as evidenced by how the two readers physically position themselves in relation to each other and the device. This wider compass is important because typical early reading involves triadic interaction in existing close relationships, in a cultural context, rather than being ahistorical, individual encounters between brains and words.

For traditional paper books, the typical transition period from shared reading to reading independently and alone usually occurs around the age of 7 to 9. At this point, children become able to choose books for themselves, to develop preferences, to start reading 'chapter books' independently, and to decide how much time they wish to spend reading. This age also marks a gradual shift from parent-led to child-led reading, with parents in a Book Trust survey reporting a drop in reading bedtime stories to their children, from 86% at 5-years-old, to just 38% at 11-years-old (Book Trust, 2016). Taking a school book home for shared reading is standard practice in the UK and elsewhere, supporting both literacy development and shared enjoyment through parent—child interaction. The significance of this phase in literacy development is demonstrated through statistics on book and computer use; book reading drops sharply at about the same rate as digital media consumption rises: (Egmont, 2013). This period of concurrent transitions, from shared to independent reading, and from reading for pleasure to multi-media usage, makes this age group of particular interest in investigating differences in reading experience between paper and screen.

In this study, we addressed potential differences between shared reading of digital and paper texts, when children are reading and being read to, in four inter-related areas:

Cognitive: Do children differ in the quality of their descriptive and structural recall for texts read on screen and on paper? Do they differ in their attentional engagement with the story between the two media, when reading and when being read to?

Interactive and affective: Are there differences in the warmth of mother-child interactions between screen and paper media, and depending on who is reading? Do mothers provide different kinds of verbal support according to medium and reader?

Postural synchrony: Are there coherent differences in the physical positioning of mother and child when reading from screens vs. paper?

Attitudinal: do mothers and children have different experiences with, and attitudes to shared and independent reading on screen and on paper?

The literature on reading traditional paper books with children ranging from toddlerhood to around age 10 focuses mainly on cognitive factors, and shows that shared reading aids children's learning, e.g., of vocabulary (for a meta-analysis see Flack, Field, and Horst, 2016, under review). Dialogic reading styles, where the adult engages in conversation about the story, are particularly helpful for learning and engagement (e.g., Reese and Cox, 1999), and for engendering a love of reading (Bus, 2001). Most comparative studies with e-books involve digital devices designed to support independent reading through audio, multimedia content, and games (e.g., see Bus et al., 2015). These enhanced e-books are generally not designed for shared reading, and can hence become frustrating for adult reading partners (see Chiong et al., 2012). Although there is less evidence comparing children's reading from paper to more basic e-books (text on screen with minimal extra features), there is some agreement within the existing studies: Chiong et al. (2012) found lower story comprehension in 3- to 5-year-olds reading a science-themed book with a parent from an iPad than from a paper book, and Krcmar and Cingel (2014) found a small but significant drop in comprehension for pre-schoolers reading with a parent on an iPad compared with paper. In both cases, the screen reading prompted more conversation about the processes of reading, likely at the expense of story-relevant comments. Similar findings about conversation type and comprehension were reported for 3- to 5-year-olds co-reading with adults (Parish-Morris et al., 2013), and also in a comparison of parents reading stories on paper vs. laptop with 4-year-olds (Lauricella et al., 2014), although this last study found no significant difference in comprehension. The 'traditional' books in these studies were generally unornamented paper books, although books aimed at younger children in particular often have features such as texture, sound, pop-ups or flaps: books with flaps were compared to e-books by Moody et al. (2010) although no comment was made specifically on the role of these interactive paper features.

There is an abiding feeling expressed by many adults that reading an e-book provides a different 'feel' and sense of engagement from reading on paper. There are some cognitively helpful affordances of paper, such as for note-taking and studying, that are not well-replicated in electronic media (O'Hara and Sellen, 1997) but could there also be differences in the child's engagement with narrative during shared reading on paper vs. on screen? As noted above, some studies have included measures of engagement. Lauricella et al. (2014) compared parent-led shared reading of a print book and a laptop e-book in parents of 4-year-olds, and coded parent—child engagement (a broad measure combining video ratings of active vs. passive parent involvement, mutuality of communication, parental success in engaging their child, and degree of conversational turn-taking). They found higher engagement for the e-book than for the paper book, similar to findings by Chiong et al. (2012) on children's engagement with paper vs. tablet books in 3- to 6-year-olds. However, engagement as measured in these studies included physical interaction, such as page-turning processes, using a mouse or touching hotspots, which would likely be required more for touchscreens or computer mice than for paper, and it is possible that heightened excitement because of novel technology use might also be seen as greater engagement. Measures of engagement that focus more on attentional engagement with the story than on physical interaction with a device may not find the same advantages for e-books. In fact, Chiong et al. (2012) measured 'overall engagement' including parent-child interaction and enjoyment, and found more such engagement for a print book than an e-book. It is therefore unclear whether a child's engagement with a story differs between parent-led shared reading on paper and on screen. We address this issue in our study by using a measure of child engagement based not on physical movement prompted by the device, but on the child's attentional engagement with the story.

The link between affect and shared reading has been recognized in research into early (pre-school) literacy, primarily in relation to mother-child attachment security (Bus and Van Ijzendoorn, 1988; Frosch et al., 2001; Daly et al., 2015). Despite this recognition, assessment of affective aspects of shared reading in print and on screen seems to have been neglected, particularly in studies beyond infancy. Techniques to measure characteristics such as warmth are easily available in the well-established literature on family interactions involving young children, so we adapted a measure of warmth (positive affect) from the widely used Parent—Child Interaction System, PARCHISY (Deater-Deckard et al., 1997). Given the lack of previous research that focuses on warmth independently of other aspects of general interaction, we did not make predictions about differences in interactional warmth by medium, or by reader. We note in respect of reader, though, that the adult tends to have a different role when reading or listening to a child read. While the adult is in both situations in a didactic, expert role, we would expect the focus in child-led reading to be more on supporting the child's decoding than on story discussion, and this might make for lower warmth.

Warmth and attunement to the needs of the child are underlying features of the dialogic reading style, so analyzing the ways that mothers talk with their children during shared reading should illuminate ways that the type of medium and reader influence shared reading. Several previous studies of e-books have analyzed the nature of adults' comments during shared reading. Perhaps unsurprisingly, adults make more comments about the mechanics of reading (e.g., about page turns or touching screens), and fewer comments about the story itself, such as vocabulary, for e-books than paper (Chiong et al., 2012; Krcmar and Cingel, 2014; Lauricella et al., 2014). Because we looked at both mother and child as reader, we separated out mothers' comments about specific vocabulary and about the story more generally. We expected that mothers would give more support for vocabulary when the child was reading, and this might be at the expense of broader story-related comments.

Physical positioning and interactional synchrony are intrinsic, but largely ignored, aspects of shared reading. We know that more broadly, dyadic synchrony is fundamentally involved in cognitive, social and emotional development (Harrist and Waugh, 2002) and exerts a fundamental influence on the tenor and warmth of interactions. We could find little or no evidence on the role of posture and synchrony in shared reading, but we predicted that postural synchrony would have an important role to play in shared reading interactions, with the potential to illuminate differences in the experiences of reading on screen and paper. Lauricella et al. (2014) described parent—child interaction for paper and screen in terms of how parents arranged the seating. However, the use of a laptop for the e-book affected positioning in a specific way, because the laptop generally had to be placed on a table, and since there was one mouse, control could not be shared. They found that half the children controlled the mouse in the e-book condition, increasing those children's physical engagement. In the present study we aimed to reduce variation introduced by device demands by using a tablet and book with similar dimensions, which could be held and controlled in similar ways, allowing the assessment of differences in dyadic posture and synchronization between the parent and child. We also compared child-led and parent-led shared reading: given that tablet use tends to be primarily individual, we expected that shared reading with a tablet might pose challenges in sharing the device.

In summary, we compared shared reading of illustrated chapter books between mothers and their 7- to 9-year-old children, on paper or on screen, with the child or the mother as reader, to investigate four aspects of the interactions: cognitive (recall and engagement), interactive warmth and dialog, postural synchrony, and attitudes to and experience with technology.

MATERIALS AND METHODS

Participants

Participants were recruited from 10 classes in four primary schools in a semi-rural region of south-east England, where flyers were put in the book-bags of all 7- to 9-year-old children, inviting them to take part. Twenty-eight families responded to the advert, of whom 26 agreed to take part. Two children were excluded from the final sample; one with dyslexia and one who did not meet the age criterion. Parents gave written, informed consent, children gave assent, and the study was approved by the University ethics committee. In addition, parents gave written consent to use images in training or publications. When the images herein were selected, as a courtesy we obtained additional written consent from the parents.

The final sample consisted of 24 mother-child dyads, all White-British, reflecting the local population. There were 15 boys and 9 girls, with ages ranging from 7.04 to 9.89 years ($M = 8.60$, $SD = 0.91$). All of the mothers were the biological parent. Mothers' ages ranged from 30.13 to 51.53 years ($M = 41.66$, $SD = 4.61$).

To assess representativeness, parental education and household income were compared with UK Census data (2011): 83.3% of the mothers held a degree level qualification or higher, which is greater than the national average (33.9% of women). Household incomes in the sample covered the whole range, from £0-14,999 to more than £100,000. The median was £55-74,999, greater than the national average (£46,500).

Design

We used a repeated-measures design, with each pair reading one book progressively through each of the four conditions (Mother—Paper, Child—Paper, Mother—Digital, Child—Digital) for 8 min in each condition. The order of conditions was counter-balanced in such a way that the medium of reading was blocked together, as follows: two paper conditions (mother reads then child reads, or vice versa) followed by two digital conditions (in the same order of who reads), or the digital conditions followed by paper conditions. This design allowed the comparison of overall recall between reading media without the disruption of repeated changes of device.

Materials

We gave children a choice of two books, both humorous fiction works recommended for children of 7 and over: '*You're a Bad Man, Mr Gum*' (Stanton, Jelly Pie, London, 177 PP) and '*Barry Loser: I am Not a Loser*' (Smith, Jelly Pie, London, 239 pages). The first chapter of 'Mr Gum' had a Flesch reading ease score of 79.3 and the first chapter of 'Barry Loser' scored 85.8, on a 1—100 scale with 100 as easiest. The book was presented as a paperback book, measuring 260 mm × 190 mm when open, and on a Microsoft Surface RT, with a reading area of 235 mm × 132 mm. The Surface RT compared with other tablets has low reflectance and a wide viewing angle (DisplayMate Technologies, n.d.). These features are helpful in supporting shared visual access in dyadic reading. The tablet presentation used the Book Bazaar e-reading application, using the 'Publisher's Settings' option which presented the text in Tahoma typeface, providing a visual appearance very similar to the paper format. Both formats provided text and illustrations in black and white on most pages, although the ways illustrations were positioned in text varied because of different reading area sizes and automated formatting by the e-reader. The two formats differed in weight, with the book at 196 g and the Surface, including case, notably heavier at 1,020 g. The participants had all used tablets, though to different extents (see Results), but were equally unfamiliar with the Surface RT.

Measures

Cognitive

Reading accuracy

Children's reading errors were coded for the first 100 words of the child-reading condition in the digital and paper conditions. Because order of presentation varied, the words read were not identical across children, but the books did not differ systematically in readability through the book, so the accuracy over 100 words would not be expected to differ systematically across books. A reading error was defined as a: failed or non-attempt to read a word; mispronunciation; missing or inserted word; or hesitation followed by mother's intervention.

Recall

The experimenter, who was absent during the reading, checked recall at the end of reading in each medium, i.e., after both partners had read on screen, or on paper. The child was asked, 'Since you've been reading the paper/digital book, can you tell me what's happened in the story?'. This meant that each reader provided recall data twice, once after the two digital conditions and once after the two paper conditions. In order to discourage parental help, the parent was presented with a questionnaire (see below) during the child recall. Any subsequent parent-assisted recall was not included in the child's recall score.

Given our design, which aimed to support an informal and natural reading experience, children were recalling from different texts and for different amounts of input, depending on the book choice and the natural reading speed of the readers. We therefore did not score recall in terms of amount of information. We instead used 3-point scales to code descriptive detail and narrative coherence independently of the amount recalled, since the latter would depend on reading speed and fluency:

Richness of descriptive detail: 1 = no or very little information with little or no descriptive detail (two or fewer descriptive terms); 2 = some information, with three to four descriptive terms; 3 = more than four descriptive terms or details.

Narrative coherence: 1 = events or ideas not linked temporally or causally (e.g., listing unconnected ideas) no causal links; 2 = events or ideas linked as lists or with simple temporal terms (e.g., 'and then'), two or fewer causal links; 3 = More than two causal links between events or ideas.

Two raters blind to condition double-coded 10 (21%) of the recalls, achieving a satisfactory reliability, $\kappa = 0.71$, $p < 0.01$.

Video coding

Videos were coded by a researcher blind to the aims of the study and double-coded by a second coder for a randomly selected 25% of video sessions. Resulting reliability Kappa statistics are given below.

Interactive and Affective

Child engagement

Designed to capture child interest in the story, independently of differences that might occur as a consequence of different affordances of the reading device and reader. Engagement was judged from child visual attention, gesture, expression, and verbalization, and coded every minute on a scale from 1 = child distracted from story to 5 = highly engaged with story ($\kappa = 0.93$, $p < 0.001$).

Interaction warmth

The warmth of the interaction between mother and child was coded every minute on a 5-point scale, adapted from the PARCHISY coding scheme (Deater-Deckard et al., 1997), from 1 = no positive affect expressed to 5 = continuous positive affect ($\kappa = 0.82$, $p < 0.001$).

Mother comments

All mother verbalizations were coded into one of five categories:

Mechanical: referring to the digital or paper book itself, e.g., 'turn the page' 'tap there to turn'.

Vocabulary: Giving the meaning of a word, asking the child what a word means, helping the child decode a word, providing the correct pronunciation of a word.

Story: Explaining what is happening in the story, asking the child what is happening, extending the story, commenting on the story

Motivation: Encouraging child, e.g., 'well done' 'that was tricky!', keeping the child on task, e.g. 'concentrate' 'pay attention', 'you're here [pointing]' or re-reading the last sentence the child read, linking to the child's own experience, e.g., 'that sounds like your grandad!'.

Unrelated: Any utterance unrelated to the story or task.

Postural

We inspected screen shots of how participants positioned themselves with the device in each of the four conditions.

Attitudinal

Interview

Children were asked about their reading preferences and technology use at the end of the reading task. Mothers completed a paper questionnaire on the same topics which also included demographic questions.

Procedure

Families were visited at home on a single occasion by the same female researcher and assessed in as naturalistic a way as possible. Visits took place over a 5-week period at the end of the summer term and the first week of the summer holiday. Seven took place during the day, and 17 after school: we inspected the data for differences but did not see a markedly different pattern for children tested in the day. All participants were seated on comfortable sofas in their living room, except for two pairs who sat on chairs at a table. All except five children were seated on the left of the mother: it is likely that this reflected children's dominant hand preference but we did not check this. The study was explained, and parent consent and child assent gained, before the children were asked to choose which book they wanted to read, and then the pairs were asked to read aloud as they would normally. The tablet was briefly demonstrated just before the relevant reading conditions and there were no serious misunderstandings about its use or operation. The device was offered to the pair, with no instructions as to who should hold it or how they should arrange their positions. Occasionally other family members were present (a sibling as silent onlooker once, a family pet on six occasions) but no other adult humans were present. Participants were randomly allocated to one of the four orders of condition. The four conditions were completed in sequence, with a verbal recall task for the child after the second and fourth conditions. After the reading task the mother completed a paper questionnaire while the child was interviewed orally by the researcher.

Eleven children distributed roughly evenly between conditions and gender wore light activity monitors on a wrist and an ankle, and of these, three also wore a GoPro headcam, as part of a separate study. We could not detect systematic influences of wearing this equipment on behavior, other than occasional reporting of mild discomfort of a headcam and one child remaining relatively still in all conditions when wearing the activity monitors. These variables are not mentioned further.

RESULTS

Reading Choice and Accuracy

Book choices were almost evenly divided (13 Barry Loser, 11 Mr. Gum) with no significant gender or age bias in choice. In general, we found no effects of gender, book choice or condition order, and we do not report further on these variables.

Reading errors varied from 5 to 9% of words, indicating that the books were at the appropriate level, and showing no significant differences between book choice or medium of reading, both $Fs(1,16) < 1$. Children tended to progress further through Barry Loser (average progress to page 76) than Mr. Gum (average to page 57), as there were fewer words per page on average in Barry Loser.

Story Recall

There were no significant differences either in richness or coherence of recall according to text medium, each $F(1,16) < 1$, as shown in **Table 1**. There was no significant difference between the two book choices in either score, both $Fs(1,16) < 1$. The design did not enable separation of recall data by reader.

Child Story Engagement

An analysis of variance (ANOVA) for mean scores of child engagement showed a main effect of reading medium, $F(1,16) = 4.88$, $p < 0.05$. There was a small but significant difference, with higher engagement for reading from paper, $M = 3.50$, $SD = 0.16$, than from screen, $M = 3.31$, $SD = 0.19$. There was also a difference by identity of reader, $F(1,16) = 8.31$, $p < 0.01$, with higher engagement when the child was reading, $M = 3.64$, $SD = 0.19$, than when the mother was, $M = 3.17$, $SD = 0.19$. There was no significant interaction of medium and reader, $Fs(1,16) < 1$.

Interaction Warmth

A repeated-measures ANOVA on interaction warmth rating by medium and reader and by minute across the 8 minutes (using Greenhouse—Geisser *Fs* to correct for sphericity where required) showed a main effect of reading medium, $F(1,20) = 5.60$, $p < 0.05$, with a slight but significant lower overall warmth for screen reading ($M = 3.10$, $SD = 0.18$) than for paper ($M = 3.57$, $SD = 0.20$). There were no effects for mother vs. child as reader, $F(1,20) < 1$, and a main effect of time, $F(7,92) = 2.60$, $p < 0.05$. These effects were moderated by a significant interaction between medium, reader and time, $F(7,96.5) = 3.63$, $p < 0.005$. The changes in warmth across the sessions are shown in **Figure 1**. There appears to be a marked change for screen reading around halfway through the 8-min session, particularly when children read from screen. We examined the trends over time for the different conditions by running ANOVAs with trend analysis for each condition. There were no significant effects of time on interactive warmth for children reading on paper or for mothers on screen, $Fs < 1$. For children reading from screen, there was a main effect of time, $F(4.4,92.6) = 2.62$, $p < 0.05$, with a significant downward linear trend, $F(1,21) = 6.41$, $p < 0.02$, as shown in **Figure 1**. For mothers reading on paper there was also a significant effect of time, $F(3.78,75.63) = 2.96$, $p < 0.05$, with both a linear trend $F(1,20 = 5.99$, $p < 0.02)$ and a 5th order trend, $F(1,20) = 11.13$, $p < 0.005$) which we did not seek to interpret.

Maternal Commentaries

There were very few 'unrelated' comments (fewer than 3% in each condition), so we excluded these from analysis. We computed commentaries as a proportion of the total number of maternal comments, to control for differences in verbosity between conditions, as shown in **Figure 2**, and compared the effects of medium and reader using ANOVA, for each comment type. As we anticipated, mechanical comments were confined almost entirely to reading from screens rather than books, $F(1,23) = 25.70$, $p < 0.001$, with no influence of who was reading and no interaction, $Fs < 1$. Again as we would expect, mothers provided more commentary on vocabulary when the child was reading than when she read herself, $F(1,23) = 76.08$, $p < 0.001$. There was no difference between paper and screen for such comments, and no interaction between medium and reader, both $F < 1$.

Commentary about the story was reasonably frequent overall, but differed according to condition: there was a main effect of who was reading, $F(1,23) = 26.65$, $p < 0.001$, with more comments on the story when mother, rather than child, was the reader. Although not significant, we should note that the main effect of medium yielded $F(1,23) = 3.50$, $p < 0.07$, with more story comments for paper than for digital.

There were no significant effects of medium or reader for motivational comments, $Fs < 1$.

TABLE 1 | Mean and SD in recall richness and coherence (max = 3) following digital and paper shared reading.

Condition	Recall richness	Recall coherence
Paper	1.33 (0.82)	1.67 (0.82)
Screen	1.50 (0.84)	1.67 (0.52)

Postural Synchrony

All but two sessions involved mother and child sitting side-by-side on a sofa, holding the reading device either jointly or singly. Despite this uniformity, there was a range of ways that pairs divided the work of holding the device, turned pages, shared attention between text and partner, made themselves comfortable, and arranged themselves in relation to the device and their partner. These factors also changed between the different conditions, with partners altering their positions as device or reader shifted. We did not find a single method of coding these different features, since each pair had their own means of altering their differing postural relationships, but inspection of stills of the typical posture in each separate condition for each pair shows that the main contrast was between children reading on screens and mothers reading on paper. When children read from a screen they tended to hold the tablet in a 'head-down' posture typical of solo uses such as one-player games or surfing the internet (**Figure 3**, top left and top right). Temporal analysis of the videotapes shows that this 'head-down' starting position meant that mothers found it hard to share the screen, leading them to curl round behind the child in order to 'shoulder-surf' the screen, rather than adopting the 'curled up' position common when reading the paper book (**Figure 3**, bottom right). In contrast, when a mother read from paper, she often held the book between herself and the child, with the child very close to her, either tucked under her arm to facilitate visual sharing (**Figure 3**, bottom right) or in a very relaxed posture with audio sharing but little sight of the book (**Figure 3**, bottom left).

Mothers were seen to shift their positions between 'curled up with paper' and 'shoulder-surfing with tablet' or finding other ways to stretch to see the screen, to accommodate the different ways that children negotiated use of the reading device. We should note that this 'curling up' with the paper book, compared to 'shoulder-surfing' with a screen, was common but not universal, with one pair atypically closer together when the child was reading from the tablet, and more separate with mother reading the paper book. (**Figure 4**). However, this child was one of the youngest and therefore needed more help when reading.

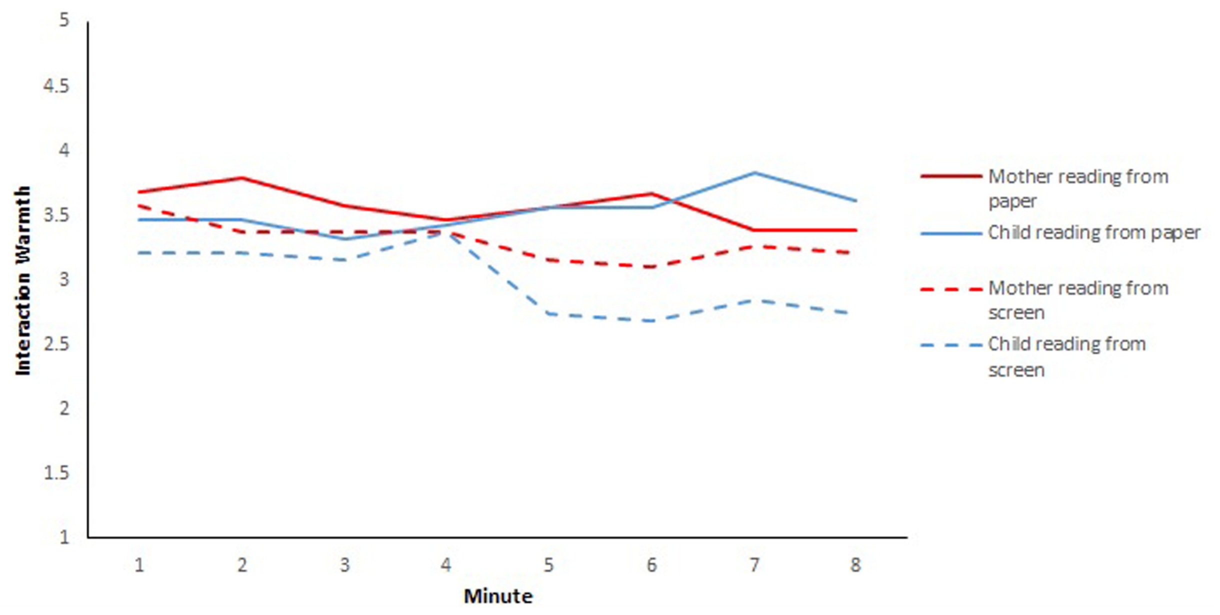

FIGURE 1 | Interaction warmth per minute for paper vs. screen with mother or child as reader (max = 5).

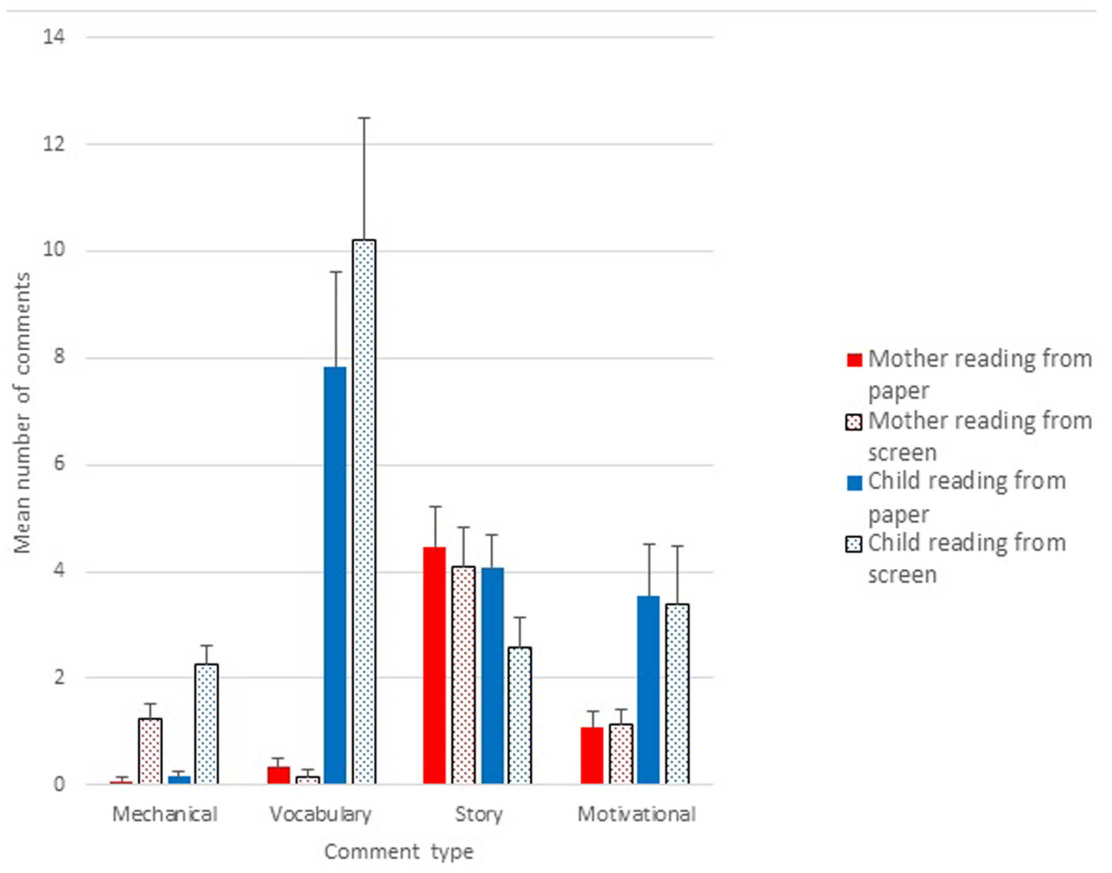

FIGURE 2 | Proportion of mother comments of each type for reading from paper and screen, with mother or child as reader.

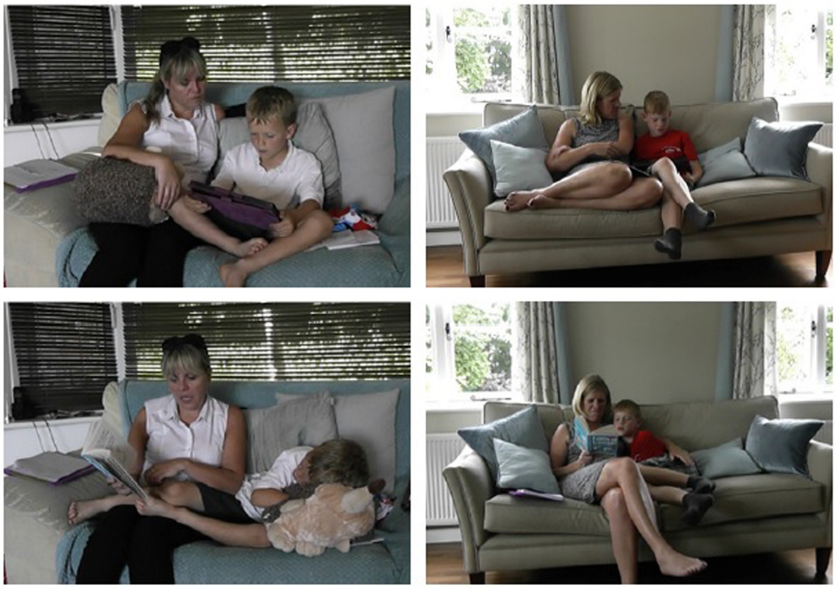

FIGURE 3 | Curling up with paper, shoulder-surfing with screen: postures for mother reading from paper (bottom) to child reading from screen (top). Consent was obtained for use of these images.

Attitudes and Digital Experience

Mothers overwhelmingly expressed a preference for reading on paper, whether this was for reading themselves or for their child as reader, as shown in **Table 2**. Children were more mixed in their opinions, being fairly evenly split regardless of reader. Of the children, seven consistently preferred screen and nine consistently chose paper, and there was a slight tendency for paper to win out when the child was reading, with four children preferring paper for their own reading and screen for their mother reading and only one showing the reverse pattern. There were no marked gender differences in these figures.

All children (except 1 non-responder) reported having access to a tablet or computer plus television at home, and most had more devices than these. Twenty-two of 24 children used at least 1 available digital device for games, but only one child mentioned use of such a device for reading, despite all children reporting reading every day. Ten of the children reported reading at home with a parent, all using paper, not screens. Sixteen children reported reading mostly fiction, and only one child reported exclusively reading factual books.

For children's reported activity at school, 16 of 24 reported reading there every day, and all but one of these was exclusively on paper. Tablets (largely iPads) and/or laptops were in reported use at school for 19 of the 24 children, largely for educational games. No child reported shared story reading on a tablet either at school or in the home.

DISCUSSION

Many studies have investigated differences in children's experience of shared reading from screens vs. paper, but primarily addressing only individual cognitive factors. Furthermore, the majority focus only on parent-led shared reading, where the child is being read to by the adult, rather than both parent-led and child-led shared reading. We observed both types of shared reading to examine not just cognitive measures of recall and story engagement, but also measures designed to capture other aspects that we believed were important to the child's experience of shared reading: interaction warmth, parent commentary, postural synchrony, habits and attitudes to technology. We summarize the main findings of our study, and their novelty, and then discuss each of these aspects in turn, followed by remarks about design and questions for further research.

We found that reading interactions involving a screen showed slightly but significantly lower warmth than those with a paper book, and warmth dropped over time for screens, particularly when children rather than mothers took the role of reader. Further, children showed higher story engagement with paper than with screen, and there was suggestive evidence that mothers also made more story-relevant comments with paper books. The two media were associated with different positioning for mother and child: a qualitative analysis suggested that child readers held and used tablets in ways more typical of individual use, so that mothers had to 'shoulder-surf' the screen, whereas mothers read paper books in ways that supported shared visual attention, enabling the child to adopt a range of curled-up postures. We found no differences in narrative and descriptive aspects of story recall for stories shared on paper or screen, whether the mother or child was reading.

Child-led shared reading showed different patterns from mother-led reading: children were more engaged with the story when they read themselves rather than when their mothers read, and mothers provided differentiated commentary, with more

FIGURE 4 | Atypical pattern of surfing with paper, curling up with screen. Consent was obtained for use of these images.

vocabulary support and less story-focused commentary when the child was reading than when reading herself. Mothers almost exclusively preferred reading from paper, for themselves and for their child, while the results for children's preferences were more mixed. Despite this, in their everyday practice parents and children reported almost always reading on paper, whether alone or during shared reading.

Our study demonstrates the value of using a broader array of measures based on a wider appreciation of the factors that influence children's experience of naturalistic shared reading in everyday settings. In the interests of providing a reading experience as typical, smooth, and motivating as possible, we allowed children a choice of books and had them read in each condition with the same book, meaning that we did not control for content or amount read across the sample. However, the identity of the book did not appear to have any systematic influence on the results, and we believe that the choice and freedom of movement provided for participants enabled us to see an illuminating variety of physical synchrony between mother, child and reading device that informed our analysis. However, our sample was small, very homogeneous and in a narrow age-range, so deserves replication and extension with a more diverse range of groups, settings, and texts.

TABLE 2 | Expressed preferences for paper or screen by reader, for mothers and children. (*N* = 24, with remainder of participants expressing no preference).

	Mother reading		Child reading	
Medium	**Paper**	**Screen**	**Paper**	**Screen**
Respondent				
Mother	22	0	21	2
Child	11	11	13	10

The context of early reading is a shared one during which children gradually develop into independent readers. Our results demonstrate that, in light of this, it is important to consider not just the potential cognitive influences of paper vs. screen (e.g., recall), but also whether the reading medium influences wider cognitive properties such as engagement with the story, and interactional aspects such as warmth. We suggested that the affective differences we found were linked to the different physical positioning of mother and child in paper and screen reading. Our results demonstrate the validity of this approach, given that reliable and significant differences were identified in the extended measures, while we found no difference in standard cognitive aspects of recall.

We now turn to discussing each aspect of the interaction by medium: recall, attentional engagement, interaction warmth, maternal commentary and postural synchrony, and previous experiences with technology and reading. We also comment on differences between mother- and child-led shared reading and discuss possible implications for design.

Previous studies have shown varying results for the cognitive factors of children's story recall and comprehension when reading from paper or screen: for example, De Jong and Bus (2002) found better learning of content for pre-schoolers being read to by an adult from a paper book than from an e-book, but Takacs et al. (2014) noted that e-books can support word learning and story comprehension just as well as print stories when they use well-designed multi-media extras. Our study used digital texts with no multimedia extras, in order to compare paper to screens more directly in relation to recall, and yielded no difference by reading medium. Mothers provided fairly frequent commentary about the stories in all conditions, and this high level of support might have reduced any differences in recall that might otherwise have occurred. In our study, we used only a 1 to 3 scale of narrative coherence and descriptive richness, to allow comparison of children who had read different amounts of text. It may be that more nuanced measures, and measures across longer time periods, would pick up subtler differences in qualities of recall than recall counts alone. For example, Mangen and Kuiken (2014) found that adults reading text on an iPad self-reported lower narrative coherence than readers on paper. Given the mixed results on recall for screen reading, it seems that any such differences are neither simple nor compellingly large.

Our results on interactive warmth are novel. Although we did not predict the lower warmth for screen reading, it was consistent with the pattern of results from our other measures.

Reading on screens was associated with lower engagement of the child with the story and elicited a higher proportion of maternal comments about the mechanics of reading. There was a hint (not significant) of fewer maternal story-related comments for shared screen reading, a pattern also suggested by results of some previous studies. We suggested that the different postural arrangements of mother and child with the different media might support these different qualities of interaction. These findings deserve further research.

Our observations of the reading sessions suggested that posture, and how readers held the reading device, influenced the tenor of the interaction. The typical posture for an adult when children read on screen was a 'shoulder-surfing' one, which seems to be a consequence of the fact that when children are actively engaged with reading from the screen, their body position tends to be perched, head down, over the screen in a way that makes it difficult for the adult to see or join in – even in the present study where we used a device in landscape format with similar dimensions to the paper book. From our own observations and experience working with children sharing devices, we have found that children are often reluctant to cede control of a digital device, perhaps because they justifiably see themselves as 'digital natives', an impression supported in this study both by mothers' comments about their children's use of screens and by children's commonly expressed preference for reading from screen (see also Yuill et al., 2013 on children sharing iPads). Books seem not to present the same impulse for control: when the pair read a paper book, it seemed natural to open the pages wider to invite the listener to curve inwards and share. When the adult read on paper, we observed that children sometimes adopted a more passive back-seat role, curling up under the mother's arm or stretching out, sometimes not even in view of the book, but listening, with their upper limbs no longer poised to hold the book or to act, e.g., to turn pages. It may be that these postures more closely reflect their role if shared reading happens at bedtime, with the child lying in bed, distant from the book. Such behaviors will reflect both the cultural practices and habits tied to the reading device – for example, the primarily individual use of tablets – but also the physical properties of the device in relation to its use. Thus, the tablet we used was considerably heavier than the book, and so some children found it easier to hold it in both hands, so a child who needed a hand free to run a finger under the line of text had to manage the device differently. We propose that differences in posture reflect both physical properties of the devices and the powerful cultural practices and habits tied to the devices. The way the device is held has implications for how easy the device is to share, and this can influence the closeness of the interaction.

We now turn to implications for design and further research. Our study is novel in addressing child-led shared reading, a context that is common during children's extended transition to independent reading. It is notable that children showed more engagement with the story when they were reading themselves than when being read to, although our design did not enable us to see whether this difference was associated with differences in recall or comprehension. It seems plausible that story memory might be better when the adult reads, given the effort required by these emerging readers when required to decode the text themselves. This is a question for future research. As we might expect, mothers gave different verbal support when the child was reading than when she read herself: children were given help with vocabulary and decoding when they read, perhaps leading to a relatively small number of comments about the story content itself. Thus, the identity of the reader taps different requirements, even though, for paper at least, interactions appear equally warm with either reader. Our sample all volunteered for the study, so are likely to be families comfortable with shared reading, and results might be different with other samples, and indeed with other family members, such as fathers.

The number of parents reading to their children seems to reduce sharply during the transition to independent reading, and adult reading is generally a solo activity. Designing e-books for sharing has therefore not been a primary focus. E-books can provide digital traces of previous readers, such as text items highlighted and definitions checked, unlike print books, but e-books do not capitalize on the interactive processes that are typically part and parcel of children's shared book reading experience when they curl up to read a good book.

Children in our study, in common with many other children, used tablets and laptops very extensively both at home and at school. They also generally read on paper daily, and with enthusiasm, both alone and with their parents, sharing reading roles. However, the use of digital technology and the activity of reading seemed to exist in two somewhat separate spheres. Children were fairly evenly divided between how much they reported enjoying their experiences of reading on screen and on paper during the study. However, this did not reflect their customary reading practices, for which they overwhelmingly reported preferring paper. These self-reported preferences are reflected in our child engagement findings: children were rated as more engaged in shared reading from paper than from screens, and when they were reading rather than being read to. This may suggest that, because digital devices are so often used in solo situations (in contrast to the typically shared use of books in the early years), reading books on digital devices moves from a potentially shared activity to a more individual, private activity.

If digital texts are to be used for shared reading, then their features could be designed to support this more effectively. Krcmar and Cingel (2014) report some frustration experienced by adults using e-books for shared reading, and several studies (e.g., Lauricella et al., 2014), including our own, report more parental talk about the mechanics of reading for screen than for paper. Our e-reader was not designed with the needs of emerging readers in mind. In particular, children's imperfect control and coordination of eye movements means that they often find it helpful to run their finger below the line of text they are reading: clearly this can prove frustrating with many e-readers, as it will produce unintended effects such as accidental page-turns. Even basic digital features can prove distracting: for example, some children were intrigued by the electronic page-turning effects, with a child in our pilot work becoming particularly engaged with playing with the page turn function to produce interesting shapes on the screen. Page-turning was mentioned by some children as a feature they enjoyed, and by others as a source of frustration. Mothers' views were less variable, with many reporting that the automatic page turn function hampered their child when decoding unfamiliar words. Thus, features that were designed to remain in the background can become unexpectedly foregrounded. Their visibility can be exacerbated by the fact that there is no single standard for how e-texts operate.

The way readers arranged themselves physically round a reading device may affect how easily an adult can support young readers' word decoding. For example, an adult sitting side by side with a child can observe the child's finger traversing the words, see head posture, share the visual field and hear attempts to sound out a word, enabling them to provide help that is sensitive to the child's particular difficulty. E-readers could perhaps be designed to underpin adult support better, or to provide audio-visual cues to support synchronization of adult help in shared reading.

Children reading to adults is a typical part of early literacy development but has been rarely examined in the context of digital books, given that most research has involved younger and less accomplished readers. Comparison of children sharing paper and digital books at the transitional age of 7 to 9 is of practical import, as children in the immediately foreseeable future will need to gain independent literacy skills, even if they have access to audio-provided e-books for individual reading. Given that shared reading can clearly provide a warm and comfortable context for parent-child interaction, its potential role in fostering collaborative activity and shared emotional experience is worth considering, particularly in a context where digital media could reduce face-to-face sharing. Where everyone has their own device, there is less opportunity for co-watching and co-experiencing, but shared reading, for example, with the traditional bedtime story, provides such an opportunity.

Comparison of digital and print media is not a one-dimensional experimental variable defined by the physical properties of books or touchscreens. Each medium comes with its own set of affordances and cultural practices: for example, the models of how we acquire, archive and share digital vs. print media are quite distinct. We can lend paper books to as many friends as we like, while we may be restricted to a single loan with electronic media; we need to take a trip to the library to borrow a paper book, but can just log in to our account to borrow an e-book; a paper book tends to have a single purpose (being read, maybe being used as a paperweight or door wedge) while an e-book is often only one app on a highly multi-functional device that can also be used to book tickets, play games, work on spreadsheets, and watch films. Further, there are physical differences between books and screens, such as weight, that we can expect to influence the embodied experience of shared reading. The role of such differences is increasingly recognized in embodied approaches to cognition and interaction (Thelen and Smith, 1994).

The cultural significance of devices is a useful reminder that studies of children's e-reading are being carried out during a time of very rapid technological change: for example, light, flexible screens will change reading postures markedly, altering shared reading in new ways. In earlier studies of e-readers, the technology has tended to be novel, and hence perhaps motivating, and this novelty factor may be less compelling in more recent studies. Our sample, for example, were all very familiar with tablets: indeed, some parents commented on how pleasant novelty of sharing a paper book with their children. In line with previous studies (e.g., Lauricella et al., 2014), we found greater frequency of 'mechanical' comments about the process of reading in the screen condition, and this is to be expected when operation of the technology, e.g., of page-turning, is familiar, but less stable than the equivalent mechanism in a paper book. It is important to consider specific design of the technology in studies of digital literacy: for example, mouse interfaces (as in Lauricella et al., 2014) provide very different mechanisms of shared control than touchscreens.

Our findings of differences in warmth over time for paper versus screen reading, and the suggested influence of physical properties and cultural affordances of screens shows the value of considering shared reading and digital text in terms broader than just the cognitive. In particular, differences in warmth are of interest given the powerful role of parent—child relationship quality for a whole range of cognitive and social outcomes (O'Connor and Scott, 2007). Studying shared reading in terms of cognition, affect, posture and embodied interaction, with an eye to the cultural practices of reading devices, should help us understand and design better reading experiences as part of children's development into independent reading in the context of their family relationships.

ETHICS STATEMENT

This study was carried out in accordance with the recommendations of the University of Sussex Sciences and Technology C-REC with written informed consent for adult and child from all adult participants and assent from their children. Adult participants gave written informed consent in accordance with the Declaration of Helsinki. The protocol was approved by the University of Sussex Sciences and Technology C-REC.

AUTHOR CONTRIBUTIONS

NY planned the main research questions and methods, analyzed the data and drafted the paper. AM planned the precise details of method, was responsible for recruitment, data collection, data input, video coding schemes and reliability, and provided material and commentary for drafts.

ACKNOWLEDGMENTS

We are very grateful to the participants and schools involved in this research, to Egmont Publishing for providing the e-book content, Zoe Flack, and Georgia Leith for pilot testing, Kate Appleby and Lauren Rowse for coding support, ChaTLab, Yvonne Rogers and Matt Jaquiery for constructive comments.

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Conflict of Interest Statement: NY received financial support from Egmont Publishing for a separate pilot study using 3 texts provided by Egmont, which was carried out otherwise as independent research. The method of the current study was informed by that study and used two of the same texts, but the work reported in the current paper was carried out entirely independently. The other author declares that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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published: 22 November 2016
doi: 10.3389/fpsyg.2016.01773

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The iPad as a Research Tool for the Understanding of English Plurals by English, Chinese, and Other L1 Speaking 3- and 4-Year-Olds

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Specialty section:
This article was submitted to Developmental Psychology, a section of the journal Frontiers in Psychology

Received: 15 June 2016
Accepted: 28 October 2016
Published: 22 November 2016

Citation:
Xu Rattanasone N, Davies B, Schembri T, Andronos F and Demuth K (2016) The iPad as a Research Tool for the Understanding of English Plurals by English, Chinese, and Other L1 Speaking 3- and 4-Year-Olds. Front. Psychol. 7:1773. doi: 10.3389/fpsyg.2016.01773

Learning about what young children with limited spoken language know about the grammar of their language is extremely challenging. Researchers have traditionally used looking behavior as a measure of language processing and to infer what overt choices children might make. However, these methods are expensive to setup, require specialized training, are time intensive for data analysis and can have considerable dropout rates. For these reasons, we have developed a forced choice task delivered on an iPad based on our eye-tracking studies with English monolinguals (Davies et al., 2016, under review). Using the iPad we investigated 3- and 4-year-olds' understanding of the English plural in preschool centers. The primary aim of the study was to provide evidence for the usefulness of the iPad as a language research tool. We evaluated the usefulness of the iPad with second language (L2) learning children who have limited L2 language skills. Studies with school aged Chinese-speaking children show below native performance on English inflectional morphology despite 5–6 years of immersion (Jia, 2003; Jia and Fuse, 2007; Paradis et al., 2016). However, it is unclear whether this is specific only to children who speak Chinese as their first language (L1) or if younger preschoolers will also show similar challenges. We tested three groups of preschoolers with different L1s (English, Chinese, and other languages). L1 Chinese children's performance was below both English monolinguals and children speaking Other L1 languages, providing evidence that English inflections are specifically challenging for Chinese-speaking children. The results provide further evidence to support previous eye-tracking findings with monolinguals and studies with older bilinguals. The study provides evidence for the usefulness of iPads as research tool for studying language acquisition. Implications for future application of the iPad as a teaching and intervention tool, and limitations for the method, are discussed.

Keywords: iPads, preschools, early child second language learning, plural inflectional morphology, Chinese-speaking children

INTRODUCTION

One of the challenges in language acquisition research with toddlers and preschool children is creating age-appropriate and engaging experiments. Young children are limited in both their cognitive and linguistic capacity to follow instructions and maintain attention. Therefore, researchers working with very young children have traditionally relied on analyzing children's looking behaviors as a proxy for assessing the acquisition of grammar. One such method used to examine early linguistic representations is the intermodal preferential looking (IPL) paradigm (see Golinkoff et al., 1987). In a typical IPL task, children are presented with two pictures side-by-side on a screen. After some time to familiarize themselves with the pictures, children are then played an auditory instruction which matches one of the two pictures. Looking behavior is then analyzed before and after hearing the auditory instruction, which reveals children's comprehension of the linguistic structure being tested. For example, when testing children's understanding of nominal plurals, one might show a picture with a single novel object (singular picture) and another picture with five identical new novel objects (plural picture). Upon first viewing the pictures, children's looking behavior should be random. However, if children understand plural morphology, they should increase looks to the plural picture after hearing auditory instructions such as '*look at the teps.*' Originally, test sessions were video recorded and children's looking behaviors were manually coded frame by frame in a labor-intensive process. Today, many studies are being conducted using an eye-tracker, where the recording and processing of data can be largely automated. However, we still lack knowledge about what overt choices young children might make on such a task, and how this might relate to looking behavior. Children often show behavioral responses that do not match their looking behavior when they are developing early sensitivities to linguistic structures (Sekerina et al., 2004). Even less is known about the performance of 3- and 4-year-olds on these measures, when the ability to understand and follow instructions is only beginning to emerge (see Trueswell et al., 1999; Sekerina et al., 2004, for studies with older children).

Eye-tracking studies often have considerable dropout rates of 10–50%, depending on the task and ages of the children been tested (Kouider et al., 2006; Mulak et al., 2013; Davies et al., 2016). This can lead to skewed and unrepresentative data. Furthermore, laboratory based studies often have low participation rates, since coming into the lab is not feasible for many busy working parents. There has therefore been a need to find an alternative testing paradigm whereby large numbers of children can be tested quickly with low dropout rates. To ensure high rates of participation, it would be ideal to develop a reliable method for testing children outside of the laboratory at preschools and schools. In recent years, there has been widespread acceptance of touch pad technology, including with young children, who seem to have a good understanding for the concept of making a choice by touching a picture. The touch pad is also extremely portable and easy to use. Furthermore, children appear to be interested in engaging with the touch pad. This is especially important for young children with very limited attention spans; keeping them engaged is an important part of any experimental design. Given these obvious advantages in using the touch pad as a research tool, we developed a series of studies that aimed to replicate IPL and eye-tracking studies on the Apple iPad to test children in preschool settings. In the series of studies reported here, we tested the acquisition of nominal plural morphology by English-speaking monolinguals and Chinese-speaking children learning English, as well as children who speak a variety of different L1s other than English and Chinese.

The acquisition of nominal plural morphology has attracted attention in research with young children as one of the earliest acquired aspects of inflectional morphology in English (followed by present and past tense; Berko, 1958; Brown, 1973; de Villiers and de Villiers, 1973). Adult speakers of English know that the plural *cats* can be decomposed into the root stem *cat* and the plural morpheme *-s*. They are aware of morphological variants of the plural, i.e., the plural morpheme in *cats* is /s/, a voiceless fricative, in *dogs* it is /z/, a voiced fricative, and in *horses* it is /əz/, a full syllable. While the use of plural morphemes in obligatory contexts has been reported in the speech of 2-year-olds (Brown, 1973; de Villiers and de Villiers, 1973), testing their productive knowledge of plural morphology has been challenging. Many preschool aged children are unable to perform the wug task, e.g., presenting the singular stem *wug* and asking children to provide the plural form *wugs* (Brown and Berko, 1960; but see Zapf and Smith, 2007). For this reason, many researchers have used the IPL paradigm to test children's acquisition of plural morphology. Using this paradigm, one study found that both 2- and 3-year-olds show an understanding of plurals, as indicated by increased looks to the corresponding singular/plural picture after hearing the auditory instructions, e.g., "look there are some *blickets*" (Kouider et al., 2006). What is unclear is whether these children are using other plural cues, e.g., the copula *is/are* or the determiner *some* rather than nominal plural inflectional morphology (*-s*) to perform this task. To test this, the same aged children were given only the nominal inflectional morphemes, "look at the *blickets,*" and only 3- but not 2-year-olds increased looks to the plural picture (Kouider et al., 2006). The results suggest that a full understanding of nominal plural inflectional morphology is acquired late, but that there might be differences in children's sensitivity to the different plural allomorphs, e.g., /s/, /z/, and /əz/. A recent study addressed this question by testing 2-year-olds with the plural allomorphs /s/ and /z/ (Davies et al., 2016). The results showed that 24-month-olds *do* demonstrate an understanding of plural inflectional morphology, but only for the voiceless fricative plural allomorph /s/ and not the voiced fricative /z/, e.g., *teps* but not *degs*. A follow up study examined the acquisition of the syllabic plural /əz/ (e.g., *tizzes*) and found that 36- but not 30-month-olds show sensitivity to this allomorph (Davies et al., under review). Together these studies suggest that the acquisition of English nominal plurals is a gradual process, with some allomorphs (/s/) acquired earlier than others (/z, əz/). Understanding that *tep* refers to a single object also emerges at around 3-years, suggesting that the grammatical understanding of singular vs. plural morphology develops during the 2–3-year-old period.

These results from monolingual children provide an important baseline for assessing the grammatical development of bilingual and early child L2 (ECL2) learners. Several recent studies of ECL2 learners report continued challenges in using inflectional morphology after many years of exposure to English. For example, Paradis et al. (2016) found that Chinese-speaking children who began learning English at the age of 4 years continue to show difficulties with inflectional morphology after 6 years of English exposure. Some of the structures tested include tense inflections, e.g., past tense '*she cooked,*' and third-person singular *-s*, e.g., "*she cooks now.*" These results are consistent with studies on older Chinese Mandarin-speaking children who began learning English at school (Jia, 2003; Jia and Fuse, 2007). Jia (2003) concluded that some children were unable to attain monolingual-like usage of plurals or tense marking even after 5 years of exposure. In contrast, studies with children from other L1s, including Turkish, Spanish and Punjabi, show good performance on L2 English inflectional grammar during initial acquisition and over time (McDonald, 2000; Marinis and Chondrogianni, 2010; Paradis, 2011; Blom et al., 2012). However, these languages are rich in inflectional morphology, unlike Chinese. For example, the plural in Chinese is marked with a numeral, a modifier, and a noun [e.g., *one modifier cat* vs. *many (optional modifier) cat*]. In English, plurals are inflected with one of the plural allomorphs *-s* or *-es* (e.g., *cats, horses*). Unlike Chinese, English-speaking children must learn that a plural word (e.g., *cats*) is composed of a stem (*cat*) and a plural morpheme (*-s*). This is not required in Chinese and therefore ECL2 learners might find English inflectional grammar challenging. However, so far there have only been studies comparing L2 children with monolingual controls; no study has directly compared the performance of Chinese and other L1 speaking ECL2 learners on inflectional morphology. This is required to understand the effect of L1 Chinese vs. other L1 languages on L2 English acquisition. In addition, studies on L2 acquisition typically use standardized tests, which provide global measures but are not sensitive to fine-grained information like the gradual acquisition of plural allomorphs.

In this study, we addressed these questions using a cohort of monolingual and ECL2 learners speaking L1 Chinese and other languages. In collaboration with Toybox Labs, a series of studies were designed and delivered on the Apple iPad which were based on laboratory based eye-tracking studies (Kouider et al., 2006; Davies et al., 2016, under review). The main aim of the study was to evaluate the usefulness of the iPad as a language research tool, especially with ECL2 learners who have limited L2 English abilities. In order to be a useful research tool, it must have reasonable inclusion rates compared to laboratory-based studies and sensitive for measuring children's understanding of linguistic structures, e.g., plural morphology. These evaluations are essential and timely because the iPad is portable and easy to use, and could potentially allow large numbers of children to be tested quickly at preschool centers. The method was applied here for assessing L1 Chinese and other L1 speaking children's performances on L2 English plural morphology. Based on previous iPad studies we expect that the English monolinguals should perform well above chance on all tasks. Given that 2-year-olds are already showing sensitivity to some plural morphemes, English monolingual 3- and 4-year-olds in this study might show close to ceiling performance. However, both groups of ECL2 learners might show lower and more variable performance compared to English monolinguals. If L1 Chinese constrains the learning of inflectional morphology, then Chinese-speaking children should perform worse than English monolinguals and other L1 speaking children. However, if learning English inflectional morphology is challenging for all ECL2 learners regardless of their L1, then both groups of L1 children should perform worse than English monolinguals. In addition, L1 Chinese children might have better performance on the singular items compared to plural inflected items. This is because singular nouns are not marked with inflections and should be readily acquired by Chinese-speaking children.

MATERIALS AND METHODS

Participants

This study was carried out in accordance with the recommendations of the 'Macquarie University Human Research Ethics Committee' with written informed consent from all parents of the child participants. Language history questionnaires containing questions about children's language exposure, family socio-economic status, parental education and whether they had any hearing or developmental delays, were also collected.

The study accepted all 3- and 4-year-olds with signed consent forms as participants for the study. They were drawn from eight preschool centers around the North Sydney area. A total of 69 children (36 girls, 24 boys) participated in the study. The data from nine of these children were excluded from analyses for attempting less than 70% of the trials (six children), not reporting language background (two children) and a history of hearing loss (one child). Data from the remaining 60 typically developing children were analyzed here.

The children were assigned into three groups based on home language. Twenty-two children spoke only English at home and had a native English-speaking mother. Of these 22 children, 10 reported having exposure to another language for between 0.5 and 5 h per week. Nineteen children spoke Chinese at home and 18 had a native Chinese-speaking mother. Of these 19 mothers, 12 were born in China, 3 in Hong Kong, 2 in Taiwan and 1 in Australia and is a heritage speaker of Chinese. Another 19 children spoke a language other than English or Chinese at home[1]. Of these 19 children, 4 were trilingual. All L2 English children reporting speaking a home language other than English and were exposed to English at the preschool. The length of preschool attendance is therefore used here as the measure for length of exposure to English.

The mean age of the children was 48 months (47.5 months for English, 46 months for Chinese, and 49 months for other

[1]Languages reported include: Afrikaans, Armenian, Bengali, Farsi, Filipino, German, Gujurati, Hindi, Italian, Japanese, Korean, Kurdish, Malayalam, Marathi, Polish, Punjabi, Romanian, Serbian, Sinhala, Spanish, Swiss German, Tamil, Thai, Turkish. Of these languages, only Thai is an isolating language like Chinese.

languages). On average children had been attending preschool for 23 months (22 months for English, 20 months for Chinese, and 28 months for other languages). As a group, these children attended preschool between 12 and 45 h per week.

The education level for mothers ranged from High School to Postgraduate degrees with the majority having either an undergraduate (28 mothers) or postgraduate degree (26 mothers). The education level for fathers also ranged from High School to Postgraduate degrees with the majority having either an undergraduate (27 fathers) or postgraduate degree (22 fathers). The parents of children from the three groups were similarly represented in their levels of education.

Design

A within subjects design analogous to 2FC (two alternative forced choice) based on the IPL paradigm was used (see procedure for a full explanation). All children were invited to participate in the entire experiment consisting of three blocks. The three blocks tested children's understanding of suppletive verbal plural morphology using the copula *is/are*, segmental plural allormorphs /s/ vs. /z/, and the syllabic allormorph /əz/.

To avoid any effects of presentation order on performance, the presentation of the three test blocks were counterbalanced across participants. Pseudo-randomizations for the order of trials was also created within each block. While each block contained the same set of nonce objects/animals across the four versions, each object/animal was depicted only once as a plural target, once as a plural distractor, once as a singular target and once as a singular distractor. Pictures were not yoked so that across the four versions no two object/animals were displayed together in more than one trial. Furthermore, no auditory stimulus item was presented with any object/animal more than once across the four versions, regardless of it being a target or distractor picture.

Stimuli

Auditory Stimuli

Auditory stimuli were recorded in a single session to avoid difference in sound quality. The recordings were conducted in a sound-attenuated room and spoken by a female native Australian-English speaker using a child friendly speech register. Audio was recorded using Cool Edit Pro 2.0 sampled at 48 kHz. Stimuli were recorded as complete utterances with carrier phrases. Stimuli for the copula *is/are* test trials were recorded with the carrier phrases "where are [the X]?" and "where is [the X]?" Stimuli for all other trials were recorded with the carrier phrase "touch [the X]."

For the test trials a total of 72 nonce target words were recorded, 36 of which were singular and 36 inflected for plural. Nonce words had onset stops that are early acquired by English-speaking monolingual children: /n/, /d/, /t/, /b/, /p/, /g/, and /k/ (Smit et al., 1990). Vowels were short Australian-English vowels: /æ/, /ɛ/, /ɪ/, /ɐ/ and /ɔ/ (Harrington et al., 1997). In addition to these nonce words, 11 real words were also recorded. Real words were *fox, ducks, clocks,* and *box* in the copula block; *bat(s), crab(s), mop(s),* and *pig(s)* in the segmental /s/ vs. /z/ plural block; and *horse(s), rose(s),* and *bus(es)* in the syllabic plural block. The training block contained five trials with all singular target words: *dog, bird, cat, nug,* and *mib*. **Tables 1–3** contain the nonce words used in the test trials.

To ensure minimal acoustic differences across the auditory stimuli, splicing was conducted using Praat

TABLE 1 | Copula (is/are) test block nonce words (with and without copula).

	Singular		Plural	
No copula	dax	/dæks/	dacks	/dæks/
	gex	/gɛks/	gecks	/gɛks/
	gox	/gɔks/	gocks	/gɔks/
	bix	/bɪks/	bicks	/bɪks/
	nux	/nɐks/	nucks	/nɐks/
	poox	/pʊks/	poocks	/pʊks/
With copula	dap	/dæp/	daps	/dæps/
	doop	/dʊp/	doops	/dʊps/
	gip	/gɪp/	gips	/gɪps/
	mep	/mɛp/	meps	/mɛps/
	tup	/tɐp/	tups	/tɐps/
	nop	/nɔp/	nops	/nɔps/

TABLE 2 | Segmental plural test block nonce words (segmental plural allomorphs /s/ and /z/).

	Singular		Plural	
Voiceless plural allomorph /s/	dup	/dɐp/	dups	/dɐps/
	bip	/bɪp/	bips	/bɪps/
	tep	/tɛp/	teps	/tɛps/
	mup	/mɐp/	mups	/mɐps/
	noop	/nʊp/	noops	/nʊps/
	gop	/gɔp/	gops	/gɔps/
Voiced plural allomorph /z/	pab	/pæb/	pabs	/pæbz/
	tib	/tɪb/	tibs	/tɪbz/
	geb	/gɛb/	gebs	/gɛbz/
	mub	/mɐb/	mubs	/mɐbz/
	koob	/kʊb/	koobs	/kʊbz/
	tob	/tɔb/	tobs	/tɔbz/

TABLE 3 | Syllabic plural test block nonce words (syllabic plural allomorph /əz/).

	Singular		Plural	
/s/-final stem	koss	/kɔs/	kosses	/kɔsəz/
	nass	/næs/	nasses	/næsəz/
	poss	/pɔs/	posses	/pɔsəz/
	dass	/dæs/	dasses	/dæsəz/
	bess	/bɛs/	besses	/bɛsəz/
	giss	/gɪs/	gisses	/gɪsəz/
/z/-final stem	niz	/nɪz/	nizes	/nɪzəz/
	kez	/kɛz/	kezes	/kɛzəz/
	moz	/mɔz/	mozes	/mɔzəz/
	tiz	/tɪz/	tizes	/tɪzəz/
	doz	/dɔz/	dozes	/dɔzəz/
	paz	/pæz/	pazes	/pæzəz/

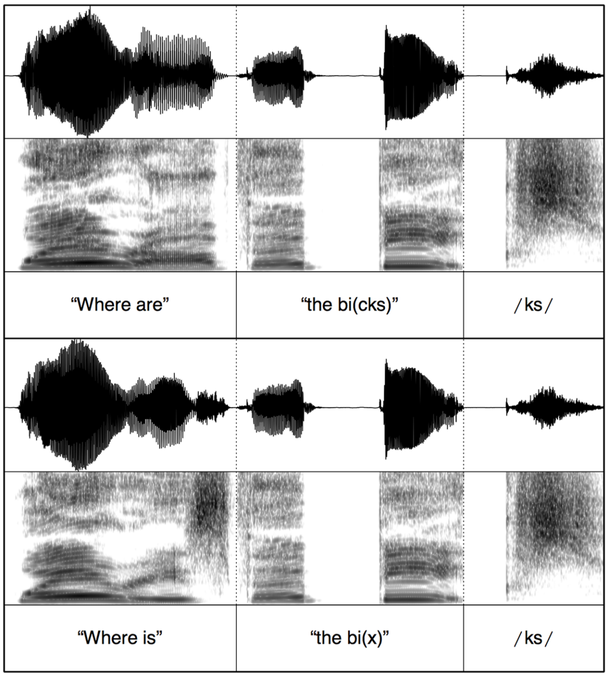

FIGURE 1 | Example stimulus splicing for auditory stimuli with the copula is/are.

(Boersma and Weenink, 2016). For each test block, the target words were spliced onto one carrier phrase. For the copula (*is/are*) test block, the spliced stimuli contained the carrier "where is" + determiner and target word stem (ending at stop closure) + burst release (e.g., /p/ in "dap") or burst release and frication from the plural morpheme (e.g., /ps/ in "daps"); see **Figure 1**. Therefore, across plural and singular trials the only acoustic difference was the presence vs. absence of the plural morpheme. Stimuli for the segmental plural /s/ and /z/ test blocks were created in a similar way, the only difference being the initial carrier phrase word ("touch"); see **Figure 2**. For the syllabic plural /əz/ test block, the entire target word (singular or plural) was spliced onto the carrier (e.g., "touch" + "the kos" vs. "touch" + "the kosses"). This is done because vowel and frication durations were different in the word stem between the monosyllabic singular (e.g., "kos") and disyllabic plural words (e.g., "kosses"); see **Figure 3**. These durational differences are naturally occurring between singular and plural real words. The splicing therefore ensured that the stimuli sounded natural.

Visual Stimuli

Visual stimuli were composed of 24 novel inanimate objects and 48 novel cartoon animals, depicted with happy faces and closed eyes. The novel objects and animals did not resemble anything real or fictional. For known trials, 22 real objects/animals were created. These included *box, shirt, duck, frog, clock, hat, cow, fox, bat, bug, pig, snake, mop, cake, crab, rat, bus, house, rose, tree, horse, and bear*. The known trials were included to maintain children's interest and were not analyzed. Visual stimuli were constructed as both one object/animal (singular) pictures and five object/animal (plural) pictures. Visual stimuli constructed for the training trials consisted only of singular animals, two of which were novel. **Figure 4** shows examples of a known animal trial (A) and a novel animal trial (B).

Equipment

The children wore Sennheiser HD 280 pro headphones. The experimental software was built using the Serenity Engine (Budziszewski, 2003) and presented on an Apple iPad Air 2 (240 × 169.5 mm, with a resolution of 2048 × 1536 at 264 dpi).

The Serenity Engine is a multiplatform engine written in C using the OpenGL library. This software makes use of Serenity's iOS port, with other versions available depending on the situation. Serenity uses the iOS native sound playing capabilities. However, its image displaying capabilities are platform independent. As the current software used a number of large image files, Serenity preloaded the images into memory before each experiment began, ensuring smooth performance throughout. After each trial, results were saved to a text file and then uploaded to an SQL database. As a result, if the experiment was stopped midway, partial results would still be available. If internet access was interrupted, or unavailable during the experiment, results were stored locally on the iPad, and uploaded to the server when internet access was made available. Results were downloaded from a web browser.

The software was designed to allow for a variable number of trials and blocks. These elements can be randomized; alternatively, researchers can pre-specify the order in which items and/or blocks are displayed. Currently, the source code must be manually edited in order to make use of these options. In future, we hope to make these capabilities more accessible to researchers through the use of a scripting language or GUI. This will enable researchers to program experiments which are tailored to their own needs. These will be available on all platforms supported by Serenity. Currently, these are iOS, Windows Phone, PC, Mac, and Linux. The experiments described in this paper will be released on the Apple Store for free, allowing researchers to replicate these experiments.

Procedure

The children were tested in a quiet area of their preschool, at a child-sized table and chairs. All children wore headphones which helped to focus them to the task, minimized noisy distractions from preschool, and to serve as a blind control for experimenters so they could not hear the stimulus items. The iPad was placed directly in front of the child. To ensure the relevant plural morphemes could be heard, children were first played an /s/ and a /z/ segment extracted from the stimuli. If children indicated they could hear both segments by repeating each sound, the experiment proceeded (if they could not, the volume was adjusted until correct responses were provided).

The initial five trials comprised the Training Block, which tested children's understanding of the forced-choice paradigm. The training trials presented children with two pictures side-by-side, both depicting a single animal. The first two trials presented the pictures *dog* vs. *cat* and *cow* vs. *bird*. After the pictures had

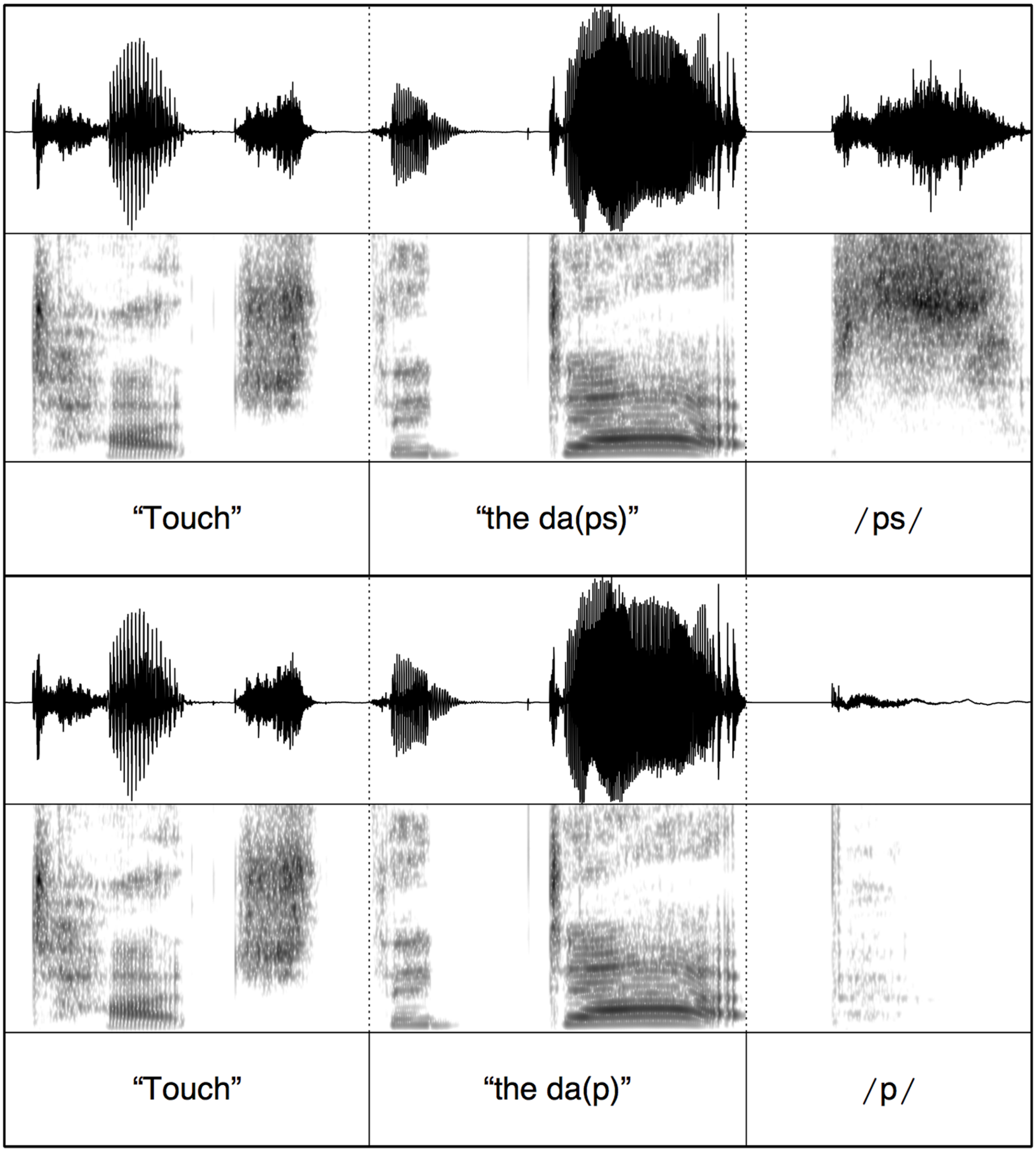

FIGURE 2 | Example stimulus splicing for auditory stimuli with segmental morpheme /s/.

been displayed for 2 s, an auditory prompt told the children to "touch the dog" and "touch the bird." The third trial presented a *cat* next to a novel animal A, and the child heard "touch the cat." The fourth and fifth training trials presented children with a *dog* vs. novel animal A, and *bird* vs. novel animal B, and had the auditory stimuli "touch the nug" and "touch the mib." Upon touching a picture, an audible chirrup would play, and the chosen picture would flash for 1.5 s. This happened regardless of whether the child chose the target or the distractor picture. During the training block, experimenters could give children positive verbal reinforcement if they appeared shy, confused or unsure.

After completing the training trials, understanding of English plural morphology was then tested in the following 47 test trials. For each test trial, two pictures were displayed side-by-side, and after 2 s an auditory stimulus played, encouraging participants to touch one of those pictures. One picture depicted a single object/animal (singular), and the other depicted five different unknown object/animals (plural). The auditory stimulus contained a nonce word that either had a CVC phonological form (e.g., "dup") to indicate a singular target, or an inflected CVCs/CVCz/CVCəz form (e.g., "teps/degs/kosses") to indicate a plural target. The use of unknown pictures and nonce words

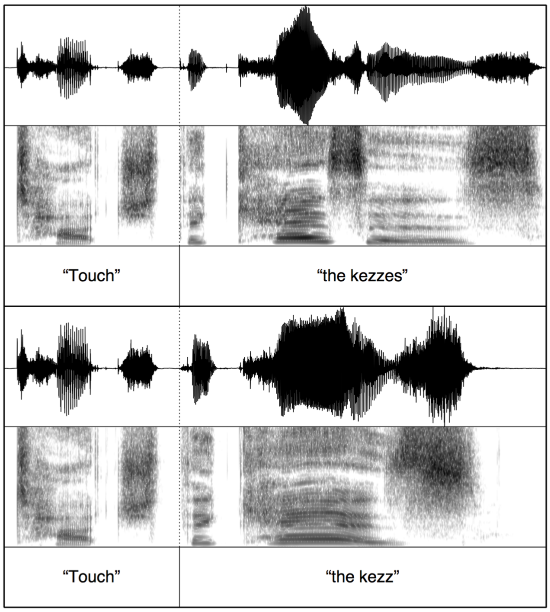

FIGURE 3 | Example stimulus splicing for auditory stimuli with syllabic morpheme /əz/.

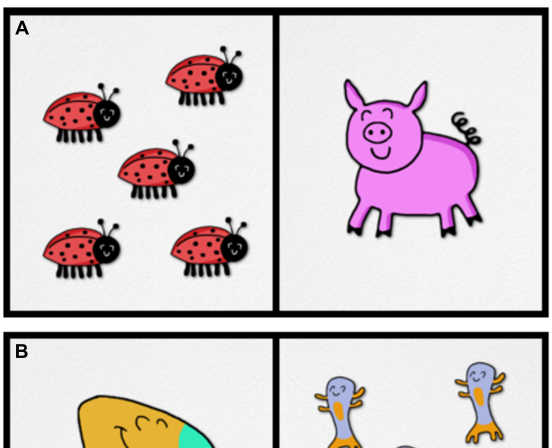

FIGURE 4 | Examples of (A) Known animals and **(B)** Novel animals.

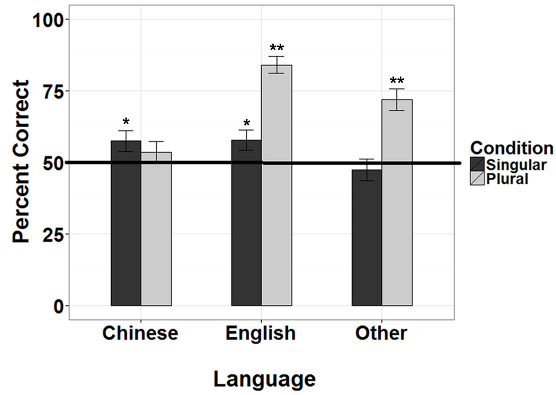

FIGURE 5 | Percent correct on singular and plural items, with performance compared to chance for three L1 groups (English, Chinese, and other languages). *$p < 0.05$, **$p < 0.01$, error bars indicating standard error of the mean and chance at 50%.

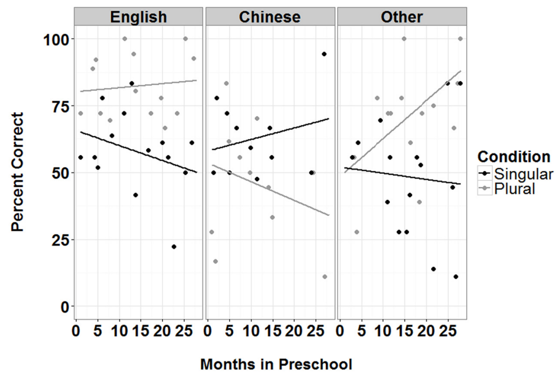

FIGURE 6 | Percent correct on singular and plural items as a function of months spent in Preschool for three L1 groups (English, Chinese, and other languages).

ensured that only understanding of plural morphology was tested and not lexical knowledge.

The 47 test trials were divided into three blocks, each of which tested a different aspect of English plural morphology. Each test block contained trials containing unknown pictures and auditory stimuli, and also known trials, which used familiar pictures and stimuli, in order to help maintain children's attention toward the task. The copula test block tested children's understanding of suppletive verbal plural morphology (*is* vs. *are*), and consisted of 16 trials (12 novel, 4 known). The segmental plural test block tested children's understanding of segmental nominal plural allomorphs /s/ and /z/ (e.g., *tep* vs. *teps*; *deg* vs. *degz*), and consisted of 16 trials (12 novel, 4 known). The syllabic plural test block tested children's understanding of the syllabic nominal plural allomorph /əz/ (e.g., *koss* vs. *kosses*), and consisted of 15 trials (12 novel, 3 known).

RESULTS

To test whether the performance of L1 Chinese children differed from that of the English monolinguals and children speaking other L1 languages, we first conducted *t*-test comparing performance on the singular and plural items against chance for each group (see **Figure 5**). For singulars, both English

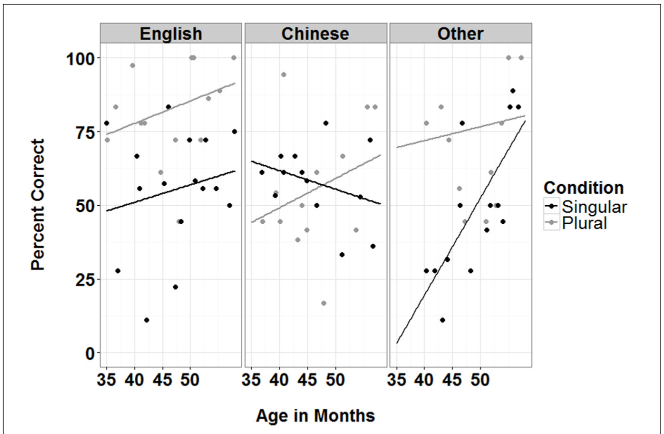

FIGURE 7 | Percent correct on singular and plural items as a function of Age (months) for three L1 groups (English, Chinese, and other languages).

(M = 57.828) and Chinese (M = 57.366) children performed significantly above chance [English: $t(68) = 1.667$, $p < 0.048$; Chinese: $t(36) = 1.688$, $p < 0.047$]. For plurals, both English (M = 83.907) and children speaking other languages (M = 71.930) performed significantly above chance [English: $t(68) = 1.667$, $p < 0.001$; Other: $t(36) = 1.688$, $p < 0.001$]. These results suggest that English monolinguals were performing above chance for both singular and plurals, showing acquisition of plural morphology. Chinese children on the other hand, were above chance only for singular items, while children speaking other L1 languages were above chance only for the plural items.

To examine the effect of L1 and morpheme type on performance, a linear mixed effects regression model (LMER) was conducted in R Core Team (2013) using the *lmerTest( )* function of the *lme4 package* with *Satterthwaite* adjustments to denominator degrees of freedom (Bates et al., 2015). The model included percent correct as the dependent variable with L1 type (English, Chinese, and other languages), Condition (Singular vs. Plural) and Test (Copula, Segmental /s/ and /z/ morphemes, and Syllabic morpheme /əz/) as the fixed factors. Each child was entered as a random variable with random intercept (see **Table 4** for results and R-code).

A significant main effect for L1 was found, and the 'L1 English' term in the model having a positive effect on the intercept suggested that over all English monolinguals performed better than L1 Chinese children, $t(330.165) = 2.853$, $p = 0.005$. There was also a significant L1 by Condition interaction. Further *post hoc* comparisons show that both English children and children speaking other L1 languages performed significantly better on plural ($M = 83.907$ and $M = 71.930$) than singular ($M = 57.828$ and $M = 47.368$) test trials [English: $t(319.165) = 5.892$, $p < 0.001$; L1 other: $t(318.840) = 5.124$, $p < 0.001$]. Not such effects were found for Chinese children. No other significant main effects or interactions were found. This suggests that performance did not differ according to Test type (copula, segmental and syllabic morphemes) for any group of children.

To investigate if age or length at preschool might have any effects on performance, LMEMs were conducted for each language group separately. Test type was removed from this

TABLE 4 | Main effects and interaction with estimated values.

Fixed effects	Estimate	Error	df	*t*	*p-value*	Significance
(Intercept)	62.339	6.178	328.716	10.090	0.000	
Main effects						
L1 English	24.024	8.420	330.165	2.853	0.005	**
L1 other	10.468	8.721	330.279	1.200	0.231	
Condition (Singular vs. Plural)	−9.613	8.212	303.623	−1.171	0.243	
Test segmental	−12.778	8.111	305.635	−1.575	0.116	
Test syllabic	−13.216	8.111	305.635	−1.629	0.104	
Two-way Interactions						
L1 English × Condition Singular	−31.296	11.136	303.237	−2.810	0.005	**
L1 Other × Condition Singular	−21.965	11.531	303.206	−1.905	0.058	^
L1 English × Test Segmental	6.484	11.010	304.695	0.589	0.556	
L1 Other × Test Segmental	6.637	11.459	304.212	0.579	0.563	
L1 English × Test Syllabic	12.140	11.010	304.695	1.103	0.271	
L1 Other × Test Syllabic	16.725	11.459	304.212	1.460	0.145	
Condition Singular × Test Segmental	19.654	11.473	304.425	1.713	0.088	
Condition Singular × Test Syllabic	20.260	11.473	304.425	1.766	0.078	
Three-way interactions						
L1 English × ConditionSingular × Test Segmental	7.094	15.609	303.849	0.454	0.650	
L1 Other × Condition Singular × Test Segmental	0.521	16.206	303.603	0.032	0.974	
L1 English × ConditionSingular × Test Segmental	−2.517	15.609	303.849	−0.161	0.872	
L1 Other × Condition Singular × Test Segmental	−19.383	16.206	303.603	−1.196	0.233	

*R-code: Lmer (PercentCorrect ∼ L1 * Condition * Test + (1 | Child)). ^Approaching significance, **p < 0.01.*

TABLE 5 | Main effects and interaction with estimated values.

Fixed effects	Estimate	*SE*	df	*t*	*p*	Significance
English						
(Intercept)	44.826	28.206	42.420	1.589	0.119	
Condition	−16.199	40.114	43.580	−0.404	0.688	
Age_mths	0.795	0.585	43.420	1.359	0.181	
Mths_CCC	0.080	0.470	43.590	0.171	0.865	
Condition × Age_mths	−0.088	0.830	44.090	−0.105	0.916	
Condition × Mths_CCC	−0.404	0.666	44.170	−0.606	0.548	
L1 Mandarin						
(Intercept)	6.762	34.308	37.580	0.197	0.845	
Condition (Singular vs. Plural)	88.955	48.446	37.290	1.836	0.074	
Age (months)	1.165	0.716	37.450	1.628	0.112	
Months in Daycare	−0.685	0.728	38.350	−0.941	0.353	
Condition × Age	−2.086	1.011	37.190	−0.640	0.460	
Condition × Months in Daycare	1.122	1.030	38.350	1.090	0.283	
L1 other languages						
(Intercept)	48.742	45.342	38.000	1.075	0.289	
Condition (Singular vs. Plural)	−144.863	64.124	38.000	−2.259	0.030	*
Age (months)	0.045	0.895	38.000	0.050	0.960	
Months in Daycare	1.265	0.628	38.000	2.016	0.051	*
Condition × Age	3.064	1.266	38.000	2.421	0.020	*
Condition × Months in Daycare	−1.809	0.887	38.000	−2.039	0.049	*

*R-code: Lmer (PercentCorrect ∼ Condition * (Age + Preschool) + (1 | Child:Condition)). *p < 0.05.*

analysis because no main effects or interactions for performance were found in the previous model. Age of the children in months and length of time since starting Preschool in months were added as the fixed variables and subjects remained as a random variable with random intercepts estimated by Condition. **Table 5** presents all main effects and interactions and their estimates as well as the R-code.

For both English monolinguals and L1 Mandarin children, no significant effects were found. For Other L1 speaking children, there were significant main effects of Condition and length in Preschool, as well as significant two-way interactions between Condition with Age and Condition with length in Preschool (see **Figures 6** and **7**). The results suggest that there were greater improvements on performance with Age for singular than plural items. The reverse was found for length in Preschool, with greater improvements in performance for plural than singular items. For Other L1 speaking children, there is a maturation effect for singulars and a length of exposure effect for plurals.

DISCUSSION

The main aim of this study was to evaluate the usefulness of using the iPad for language research. We applied this technology to investigate whether L1 Chinese-speaking children show a different acquisition pattern of L2 English plural morphology compared to children speaking other L1 languages. The tests were conducted using a novel item forced choice paradigm delivered on the iPad at preschool centers. Three groups of children were tested differing on L1: English, Chinese or other languages. The results showed that English monolinguals performed better than both groups of L2 learners. On examining singular and plural items separately, it was clear that English monolingual 3- and 4-year-olds demonstrated good understanding for plural morphology and were performing above chance on both singular and plural items, with better performance on plurals than singulars. This pattern of better performance was also found for children speaking other L1s but their performance was above chance only on plural items. This was in contrast to L1 Chinese children who were performing above chance only for singular items. L1 Chinese children's poor performance specifically in plural inflected forms, which is not shared by children speaking other L1s, reveals a specific problem with acquiring L2 inflections. This provides further support for the findings with older school aged children in Jia (2003), Jia and Fuse (2007), and Paradis et al. (2016). Our results confirm that challenges in acquiring English inflections are not a general L2 learning phenomenon but is specific to Chinese-speaking children. Their pattern of performance on the singular items suggest that Chinese children have developed good linguistic understanding for the singular but may not yet have decoded the linguistic function of plural morphemes.

The results from this study also suggest both age and length of L2 exposure effects for English L2 learning. For children speaking other L1 languages, performance on singular items increased with age, showing a developmental effect. On the other hand, their performance on plural items increased with length of L2 exposure at preschool, showing a L2 learning effect. This result is similar to previous findings from English monolingual patterns of acquisition using IPL/eye-tracking methods, where sensitivity to the **/s/** plural morpheme emerged at 2 years, but sensitivity to the singular form emerged only later, at 3 years (Davies et al., 2016, under review). However, similar effects were not observed in Chinese-speaking children, again suggesting divergent acquisition patterns for Chinese children. While the lack of any developmental or learning effect for L1 Chinese children is concerning, future studies should test older children (5- and 6-year-olds) to avoid any issues with restricted range. More studies with ECL2 learners examining different aspects of language processing, using different perception and production methods, are needed to provide a comprehensive picture of the problem, which has important implications for understanding the processes that contribute to effective L2 language acquisition and processing. Until these studies are conducted, caution must be taken in interpretation these results.

These results have several implications. One implications is for L2 learners of other isolating L1 languages (e.g., Thai), who might show similar challenges in acquiring of inflectional morphology. The expectation is that they might also show poor performance on plural items, similar to that found for the Chinese children in this study. This study was not designed to compare performance in children from different L1 typologies, and therefore does not have the power to address this issue. However, the results suggest that future studies should compare different L1s (isolating vs. inflectional complex) to further our understanding of L2 acquisition. Our findings also have practical implications for teaching L2 English to ECL2 learners, raising the question of whether more targeted training, such as that provided to children with language delay, might ensure faster acquisition of inflectional grammar by Chinese children. To our knowledge, no study has yet attempted any training programs using the iPad to intervene in the process of L2 acquisition. With the high rate of iPad use in young children, more research on the iPad as a useful language-teaching tool should be explored.

In terms of this study's primary aim, to determine if touch pads us a useful tool for language research, our study provides good evidence for this. We found the iPad to be a very engaging tool for young children. All of the children tested expressed an interest in taking part in the study. In fact, other children who were not tested (could not gain consent from parents) also expressed intense interest in playing with the iPad. We also found reasonable inclusion rates for the children who participated in the study. Of the 69 children who were tested, only six were excluded for attempting less than 70% of the trials – less than 10%. If we took a more relaxed criterion of 50% attempted trials (as is often the case in eye-tracking studies), then only two children would have been excluded. In our experience working with 3- and 4-year-olds, this level of exclusion is very low. A low exclusion rate is useful for several reasons. Most developmental studies with very young children inevitably report data on well-behaved children, with the longest attention span, highest tolerance for boring and difficult tasks and who have eyes that eye-trackers can easily track. Therefore, the data from many typically developing children have not been included in the literature on early development. In this study, where data from almost all of the children are included, we can be more certain that the results are representative of typically developing children. The low exclusion rate also allows data to be collected quickly from a large cohort of children, making it ideal for population level studies. It can therefore be extremely useful in providing much needed data on a range of L2 language acquisition issues and in studying development in general.

In terms of its sensitivity, the method is sensitive enough in discriminating among groups of children with different language abilities. However, given that the English monolinguals were not yet performing at ceiling, there might be developmental effects beyond the ages tested here. This also suggests that a forced choice task might be more difficult compared to eye-tracking. While eye-tracking tasks might reveal early sensitivities to understanding plural morphology, children's ability to make overt decisions based on their understanding of plural morphology might still be developing at 3 and 4 years. We also did not observe any differences in performance across the different tests involving copula, segmental and syllabic plural morphemes found in eye-tracking studies. This suggests that this type of test may not be as sensitive for addressing fine-grained differences in grammatical knowledge, or might require more trials. Finally, given the low exclusion rate, the iPad task might be suitable for even younger children, i.e., 2 1/2-year-olds.

CONCLUSION

The usefulness of the iPad as a research tool was evaluated by testing three groups of children with different L1s (English monolingual, Chinese, and other languages) on their knowledge of plural inflectional morphology. The results suggest that L1 Chinese children's performance was different from English monolinguals and children speaking other L1 languages. Specifically, L1 Chinese children show difficulties with plural inflected items, suggesting challenges in acquiring inflectional morphology. The results also revealed both developmental and learning effects for children speaking other L1 languages. In using the iPad we found that children were engaged, leading to lower dropout rates, is appropriate for use with ECL2 learner with limited English skills, and the results were sensitivity enough to reveal group differences in performance. This provides evidence for the usefulness of the iPad as a language research tool. Ideally, larger scale longitudinal studies with children of different L1s is required to provide a robust developmental picture of ECL2 acquisition. Perhaps now, with the use of the iPad, researchers can reach more children in preschool centers, providing population level and/or longitudinal developmental data on L1 and L2 language acquisition.

AUTHOR CONTRIBUTIONS

All authors contributed to designing the experiment and to the various drafts of this paper. The first, second and fourth authors collected the data. The first author was responsible for the data analysis, interpretation of the data, drafting the paper and updating various versions of the drafts.

FUNDING

Australian Research Council (ARC) Laureate Fellowship grant #130100014 (KD) and ARC Centre of Excellence for Cognition and its Disorders grant #CE110001021.

ACKNOWLEDGMENTS

First and foremost, we thank all of the staff and management from the eight preschool centers for their time and manpower in accommodating our studies, and for their interest in research (Acre Woods Childcare, Banksia Cottage at Macquarie University, Gumnut Cottage at Macquarie University, Essex Street Kindy, Explore and Develop at North Ryde and Macquarie Park, Kidz Prints, and Active Learning International). We thank members of the Child Language Lab at Macquarie University and our two reviewers for their helpful comments and suggestions.

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Conflict of Interest Statement: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

frontiers in Psychology

ORIGINAL RESEARCH
published: 17 November 2016
doi: 10.3389/fpsyg.2016.01800

Using Touchscreen Tablets to Help Young Children Learn to Tell Time

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Young children are devoting more and more time to playing on handheld touchscreen devices (e.g., iPads). Though thousands of touchscreen apps are claimed to be "educational," there is a lack of sufficient evidence examining the impact of touchscreens on children's learning outcomes. In the present study, the two questions we focused on were (a) whether using a touchscreen was helpful in teaching children to tell time, and (b) to what extent young children could transfer what they had learned on the touchscreen to other media. A pre- and post-test design was adopted. After 10 min of exposure to an iPad touchscreen app designed to teach time, three groups of 5- to 6-year-old children ($N = 65$) were, respectively, tested with an iPad touchscreen, a toy clock or a drawing of a clock on paper. The results revealed that post-test scores in the iPad touchscreen test group were significantly higher than those at pre-test, indicating that the touchscreen itself could provide support for young children's learning. Similarly, regardless of being tested with a toy clock or paper drawing, children's post-test performance was also better than pre-test, suggesting that children could transfer what they had learned on an iPad touchscreen to other media. However, comparison among groups showed that children tested with the paper drawing underperformed those tested with the other two media. The theoretical and practical implications of the results, as well as limitations of the present study, are discussed.

Keywords: touchscreen, learning, transfer, children, iPad

OPEN ACCESS

Edited by:
Joanne Tarasuik,
Swinburne University of Technology, Australia

Reviewed by:
Mikkel B. Hansen,
University of Southern Denmark, Denmark
Jeffrey Coldren,
Youngstown State University, USA

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Specialty section:
This article was submitted to Developmental Psychology, a section of the journal Frontiers in Psychology

Received: *29 May 2016*
Accepted: *01 November 2016*
Published: *17 November 2016*

Citation:
Wang F, Xie H, Wang Y, Hao Y and An J (2016) Using Touchscreen Tablets to Help Young Children Learn to Tell Time. Front. Psychol. 7:1800. doi: 10.3389/fpsyg.2016.01800

INTRODUCTION

Touchscreen devices are increasingly prevalent forms of technology used by adolescents and adults. The use of touchscreen technology is also prevalent in early childhood (Cristia and Seidl, 2015). According to a 2013 survey about children's media use in the U.S., 63% of children from 0 to 8 years old have smartphones to play with and 40% have tablets, most of which use touchscreen technology. The average amount of time children spend using all mobile devices, including those with touchscreens, is 67 min in a typical day. Fifty eight percent of parents have downloaded applications ("apps") for their children to use on these devices (Common Sense Media, 2013).

There has been an explosion of apps that are claimed to be educational for young children. By 2016, Apple reported that there were over 170,000 apps designed specifically for educational purposes (Apple, 2016). App developers allege that these apps can promote children's intelligence, help them obtain specific knowledge, and improve their learning performance. However, very few of these so-called "educational" apps have been evaluated and tested (Hirsh-Pasek et al., 2015). Importantly, many of these apps use touchscreen technology, but there are very few studies examining the impact of apps used with touchscreen technology on children's cognitive and social development (Romeo et al., 2003; Crescenzi et al., 2014; Cristia and Seidl, 2015; Noorhidawati et al., 2015; Huber et al., 2016). In this study, we used a time learning app (Interactive Telling Time, from Apple App Store) to explore how touchscreen influences children's learning. The topic of reading the time was selected because it was a topic in the Chinese curriculum for kindergarten, and it was determined from the participants' teachers that children at this grade level had limited knowledge about reading the time.

Retaining new knowledge and skills from interacting with tools and the environment is an important ability for human beings. Compared to traditional media (e.g., printed text), the special feature of touchscreen technology is finger-based touch or interactivity. Christakis (2014) summarized these qualities by saying that touchscreen devices are interactive, tailorable, and progressive compared to traditional toys. Hirsh-Pasek et al. (2015) suggested that touchscreen apps should be designed to promote active, engaged, meaningful, and social interactive learning. Studies have shown that the embodied touching and interactivity have significant effects on learning (Agostinho et al., 2015; Dubé and McEwen, 2015; Moser et al., 2015; Wang et al., 2015; Huber et al., 2016). The embodied cognition theory proposed that cognitive processes are rooted in the body's interactions with the world, and cognition should be understood in the context of its relationship to a physical body that interacts with the world (Wilson, 2002; Shapiro, 2010). For example, one study showed that explicit instructions to trace out elements of geometry worked examples with the index finger could enhance learning outcomes (Hu et al., 2015). Recently studies explored the relation between physical interactions with a touchscreen device and learning improvement. Dubé and McEwen (2015) asked participants to complete a number line estimation task by either tapping or dragging on a tablet. Results indicated that participants in the drag condition were more accurate than those in the tap condition. Similarly, a study with worked examples on mathematical problem-solving found that finger tracing as physical movement and interaction with the environment could enhance leaning performance (Agostinho et al., 2015). The first goal of the present study was to determine whether 5- and 6-year-olds showed better ability to tell time after using a touchscreen app designed to teach clock reading.

Many researchers have explored the possibility that the touchscreen promotes learning (Romeo et al., 2003; Crescenzi et al., 2014; Wong, 2015). One study with adults found that the interactive feature (e.g., dragging an object across the screen) could improve mathematical learning performance (Dubé and McEwen, 2015). Wang et al. (2015) showed that iPad apps can not only improve students' learning performance, but also increase motivation for language learning. Studies with 8- to 11-year-olds showed that children who learned about temperature graphs by tracing their finger on the iPad touchscreen showed better performance than a non-tracing (viewing) group (Agostinho et al., 2015). Moreover, researchers have argued that touchscreen tablets such as the iPad have the potential to promote children's literacy, such as alphabet knowledge, print concepts, and emergent writing (Neumann and Neumann, 2014). Berkowitz et al. (2015) found that using educational apps at home improves children's math achievement at school. In short, all these studies indicate that the touchscreen has positive effects on learning. For the present study, all the children learned how to tell time on an iPad with an interactive app, but were tested with three different media: iPad, toy clock, and paper.

However, the educational effect of touchscreen technology has also been questioned in some studies. For example, Dundar and Akcayir (2012) did not find differences in 11- to 12-year-olds' reading speed or reading performance via learning with printed books compared to touchscreen tablets. Chen et al. (2014) found that college students' reading performance was similar for both touchscreen tablet and paper. An investigation suggested that individuals who think more intuitively and less analytically when given reasoning problems are more likely to rely on internet through their Smartphones (Barr et al., 2015). As a consequence, it is possible that not all touchscreen technology has positive effects on cognition, with benefits depending on what we use and how we use it.

It should be noted that previous studies tried to compare touchscreen with other media (e.g., paper, computer) and other learning methods (e.g., traditional semantic-map method) to find which one is more effective (Dundar and Akcayir, 2012; Chen et al., 2014; Wang et al., 2015). By comparing the effects of touchscreen and other media, there could be no direct indication of whether the touchscreen itself has a positive effect. Therefore, the present study used a pre-test and post-test design to directly investigate whether touchscreen can improve learning performance, using the specific task of learning to tell time. The advantage of pre- and post-test is that researchers can determine the effect of an experimental intervention by post-test score minus pre-test score. In this study, we used a pre- and post-test design to explore whether children's performance can be improved after they use an iPad touchscreen app to learn how to tell time on a clock.

An important goal of touchscreen learning is that children be able to transfer the knowledge they learned from interaction with the touchscreen and use it to solve problems in real life. Moser et al. (2015) found that 2.5- and 3-year-old children had transfer deficits on a puzzle assembling task, in that they could not transfer very well from touchscreen to a real 3D situation. However, Huber et al. (2016) found that 4- to 6-year-olds could transfer what they learned about solving a problem (Tower of Hanoi) on touchscreen to physical objects. In summary, the older children (more than age 4) have acquired the ability to transfer from touchscreen media to a situation not involving the touchscreen. Based on this literature, the second goal of this study was to test the extent to which the test medium affects transfer of learning. We tested transfer of learning to a toy clock (which is similar to the iPad clock and to real life clocks) and to a drawing of a clock on paper (with paper being the most common medium used in classrooms).

In this study, we chose the app "Interactive Telling Time" as an iPad touchscreen learning material and tested 5- to 6-year-old children's transfer of learning from iPad to different media.

A pre- and post-test design was used in which all children learned about telling time by using the touchscreen, and then were tested using one of three methods. Based on the interactive feature of the iPad and the app we used (Dubé and McEwen, 2015; Hirsh-Pasek et al., 2015), we predicted that learning with the iPad touchscreen would be helpful, with post-test scores being higher than pre-test. Moreover, based on similarities and differences among the original touchscreen learning device and the test materials, we predicted that testing on the iPad touchscreen would produce better performance compared to the toy clock and paper, and the toy clock would be better than paper.

MATERIALS AND METHODS

Participants and Design

A total of 65 (32 girls) 5- to 6-year-old children ($M = 70.4$ months, $SD = 4.0$) without history of neurological or psychiatric illness participated in the current study. They were recruited from a preschool in Wuhan, China. All children used an iPad touchscreen to learn to read a clock and then each participant was assigned to one of three post-test assessment groups: iPad touchscreen ($n = 22$, $M_{age} = 71.3$ months, $SD = 3.5$, 9 girls), toy clock ($n = 21$, $M_{age} = 70.8$ months, $SD = 4.5$, 12 girls), or paper drawing ($n = 22$, $M_{age} = 69.3$ months, $SD = 4.0$, 11 girls). No difference was found among groups on age [$F(2, 62) = 1.48$, $p > 0.05$]. All children were from Chinese middle-class families (participants' family income was the equivalent of 20,000 to 40,000 USD per year) and they were given stickers for their participation. All parents and teachers signed informed consent forms. This study was approved by the Institutional Review Board of Central China Normal University.

Materials

Each participant learned to read the time on an iPad Air 2 touchscreen using an app "Interactive Telling Time." Considering the complexity of children's time conceptions and the potential difficulty of teaching them to tell time (Burny et al., 2009, 2011, 2013; Labrell et al., 2016), only the hour times (e.g., 1:00, 9:00, 12:00, which we defined having minute hand on 12) and half-hour times (e.g., 1:30, 3:30, 6:30, which we defined having minute hand on 6) were presented in the format of a 12-h clock to reduce the difficulty of the learning material. Ante meridiem (a.m.) and post-meridiem (p.m.) were not differentiated. The learning material ran on an iPad app named "Interactive Telling Time" (GiggleUp Kids Apps and Educational Games Pty Ltd). This app provided multiple modules, including several learning modules and test modules. One of the learning modules, "SET the Time," was selected to present the material (see **Figure 1**). Details of this module were as follows.

At the right center of the interface, there was a target time region that had a white background. Trials of the target time were presented in this area in visual text form [e.g., "SET TIME TO 6:00" ("将时间调整为 6:00" in Chinese)], accompanied by narration in a female voice when a learning trial initially appeared. If a participant forgot what the current target time was during the trial, he/she could touch the white region for a second narration.

The left side of the interface showed a colored lion clock. The clock face had 12 numbers, a small red hour hand, and a big blue minute hand. No second hand was included. Before the initial touch of each trial, the time on the clock face was a random "wrong" hour time or half-hour time that was inconsistent with the target time (e.g., 5:00). Learners were required to adjust the "wrong" time on the clock face to match the target time through touching and rotating the clock hands. Any adjustment of the small hand or big hand would activate a time-telling voice from the app (e.g., "five past six!").

A "SOLVE!" button was located at the bottom right corner of the interface. Once participants thought they had adjusted the small hand and big hand to the right locations, they could touch the button. If the adjusted time was correct (i.e., consistent with the target time), spoken feedback was provided in a cheerful voice (e.g., "Well done!"), then the app advanced to the next learning trial. If the adjusted time was wrong, a warning tone would be given and the present trial would not disappear, reminding the participants that they had not adjusted the time correctly and further adjustments were needed until the target time was set.

Apparatus

Three kinds of apparatuses were used to test children's learning outcomes.

iPad Touchscreen Test Apparatus

For the iPad test group, the apparatus and app were the same as the ones used in the learning phase, except that, we switched to the test module "What's the time?" (see **Figure 2A**). The clock on the touchscreen app had a lion face at the center. Again, the left side of this test interface showed a clock face identical to the learning module. No second hand or other markers for seconds (e.g., graduated bars for second hand) were included.

Toy Clock Test Apparatus

For the toy clock test group, a real colored wooden toy clock was used, with a size of approximately 25 cm × 25 cm × 5 cm (width × height × depth; see **Figure 2B**). Unlike the clock on the touchscreen app, which had a lion face at the center, the clock face on the toy was plain. It had 12 numbers, a small red hour hand, and a big blue minute hand. No second hand or other markers for seconds were included.

Paper Test Apparatus

For the paper test group, the clock face with 12 numbers of each test trial was printed in black and white on A4 paper, just like what we saw in the real classroom test (see **Figure 2C**). Similarly, the design of the clock face was simple. No second hand or other markers for seconds were included.

Procedure

The present study consisted of five consecutive phases: pre-test, instruction, learning, interference, and post-test. The whole procedure lasted approximately 20 min.

Pre-test Phase

First, the experimenter asked children to orally report the 12 numbers that were arranged in a pseudo-random order on the

FIGURE 1 | Snapshot taken from Interactive Telling Time "SET the Time" on the iPad.

A B C

FIGURE 2 | The apparatuses were used in the post-test of three different groups. (A) Test module "What's the time?" on the iPad touchscreen app used in the iPad test group. **(B)** A real toy clock used in the toy clock test group. **(C)** One of the test trials used in the paper test group.

paper (i.e., 1, 8, 3, 10, 2, 11, 5, 6, 7, 12, 4, 9). Second, one clock face printed in black and white was presented to check whether they could read the time. Then, the children were asked about their touchscreen experience (e.g., "How often do you play on an iPad, smartphone, etc.?") using a four point Likert scale. Zero points were received if the answer was "Never," and three points if "Every day." Thereafter, we presented children with 12 clock faces (similar to **Figure 2C**) with different times on a printed paper. Six of them were hour times, and six were half-hour times. Children were asked what time it was on each clock face one by one. One point was awarded for each correct answer, yielding a maximum of 12 points. Children whose pre-test scores were no more than eight were asked to attend this research.

Instruction Phase

A clock face on the iPad touchscreen app was shown to make sure that the children could correctly distinguish between the small hand and the big hand (e.g., Look, there are two hands on this clock face, right? Would you mind pointing out which one is the small hand and which is the big one?). To make participants familiar with the position and arrangement of each number on the clock face, the experimenter read out those 12 numbers in a clockwise direction and asked them to point out the numbers 12 and 6. Then, a simple instruction was given to familiarize the children with the hour times. Specifically, a rule to recognize hour times (i.e., When the big hand is pointing straight up at the number 12, we say the word "o'clock!") and two examples (e.g., You see, the big hand is pointing straight up at the number 12 and the small hand is pointing at 9, then we say "9 o'clock") were given to the children. Next, a similar instruction was given for the familiarity of half-hour times.

Learning Phase

Children spent 10 min alone learning to read the time on the iPad touchscreen app (Module: "SET the Time," see **Figure 1**). As for the 10 min learning time, first, we consulted teachers in the kindergarten and found that duration of studying the knowledge of clock in the classroom is about 10 min; second, we ran a pilot study with four children before we conducted this study, and found that there was a limited time period during which children could concentrate on what they were studying. Therefore, we finally set 10 min as the learning time. The number of learning trials was unpredictable. The experimenter recorded the number of trials of the learning phase.

Interference Phase

After the learning phase, 3 min were given to the children to write down their names by themselves and to have a rest. Based on the pilot study, we found two of the children would mutter or repeat what they had learned after learning. Thus, we add an interference phase to control the short-term memory influences.

Post-test Phase

Twelve clock faces with different time points were successively shown to the participants in a random order. Half of them were hour times and half were half-hour times. Participants were required to orally report the time as loudly as possible. Children were tested using one of three kinds of media. The iPad test group was tested on the iPad touchscreen app (Module: "What's the time?," see **Figure 2A**), but the children were not allowed to touch the screen in the post-test phase. Every time a test trial appeared, participants were asked "What time is it?" by the app system. The toy clock and paper test groups were tested on a real toy clock (see **Figure 2B**) or the paper (see **Figure 2C**), respectively. The same question was asked by the experimenter.

RESULTS

All 65 participants knew the 12 numbers and the clock face. Bonferroni adjustments were made when conducting *post hoc* multiple comparisons. Effect sizes were reported as partial η^2 values (η_p^2). One-way ANOVAs revealed no difference across test media groups in prior touchscreen experience [$F(2, 62) = 0.27$, $p > 0.05$], but a significant difference on number of learning trials [$F(2, 62) = 3.78$, $p < 0.05$]. *Post hoc* multiple comparisons showed that children in the paper test group had more learning trials than children in the iPad test group. There was no significant difference between the toy clock and paper test groups, as well as iPad and toy clock test groups. Descriptive values are shown in **Table 1**. Following are the results for three dependent variables: (a) score for telling time; (b) acquisition size; (c) acquisition efficiency.

A repeated measures ANOVA with test medium (iPad touchscreen, toy clock, and paper) as the between-participants variable, test session (pre-test and post-test) as the within-participants variable, and number of learning trials as the covariate was conducted on test scores (see **Table 1** and **Figure 3**). Score on the clock-reading was set as the dependent variables. The results showed a main effect of test medium [$F(2, 61) = 3.97$, $p < 0.05$, $\eta_p^2 = 0.12$], and a main effect of test session [$F(1, 61) = 12.71$, $p < 0.001$, $\eta_p^2 = 0.17$]. However, these effects had to be interpreted in terms of the significant interaction between test medium and test session [$F(2, 61) = 8.13$, $p < 0.001$, $\eta_p^2 = 0.21$]. Analysis of the simple effects of test session for each test medium type indicated that children in all groups had higher post-test scores than pre-test scores [iPad test group: $F(1, 62) = 71.23$, $p < 0.001$; toy clock test group: $F(1, 62) = 57.66$, $p < 0.001$; paper test group: $F(1, 62) = 20.18$, $p < 0.001$]. In addition, analysis of the simple effects of test medium type for each test session revealed no significant difference among the three groups on pre-test scores [$F(2, 62) = 0.27$, $p > 0.05$]. There was a marginally significant difference for post-test [$F(2, 62) = 2.84$, $p = 0.066$]. The paper group was significantly worse than the iPad group and toy clock group according to Newman–Keuls *post hoc* test ($p_s < 0.05$).

Acquisition size (AS) was calculated by subtracting pre-test scores from post-test scores (see **Table 1**). Taking AS as the dependent variable, a one-way ANOVA revealed a significant difference among groups [$F(2, 62) = 4.45$, $p < 0.05$, $\eta_p^2 = 0.13$]. *Post hoc* multiple comparisons indicated that children in the iPad and toy clock test groups outperformed those in the paper test group (iPad vs. paper: *Mean Difference* = 2.64, $p = 0.021$; toy clock vs. paper: *Mean Difference* = 2.19, $p = 0.076$). However, the difference between the toy clock and paper was marginal. No difference was observed between the iPad and toy clock groups (*Mean Difference* = 0.45, $p > 0.05$).

Further, acquisition efficiency (AE) was calculated by dividing AS by the number of learning trials (see **Table 1**). Taking AE as the dependent variable, a one-way ANOVA revealed a significant difference among groups [$F(2, 62) = 5.26$, $p < 0.01$, $\eta_p^2 = 0.15$]. *Post hoc* multiple comparisons showed that children in the iPad touchscreen test group outperformed those in the paper test group (*Mean Difference* = 0.75, $p = 0.007$). No difference was observed between the iPad touchscreen and toy clock groups (*Mean Difference* = 0.50, $p > 0.05$) or the toy clock and paper groups (*Mean Difference* = 0.25, $p > 0.05$).

TABLE 1 | Means and standard deviations as a function of test media.

Variables	Test media (*SD*)		
	iPad	Toy clock	Paper
Touchscreen experience (0–3)	1.18 (1.01)	1.38 (0.74)	1.32 (0.95)
Pre-test score (0–12)	2.68 (2.82)	3.19 (2.93)	3.23 (2.41)
Number of learning trials	9.73 (6.71)	14.76 (9.23)	16.14 (8.31)
Post-test score (0–12)	8.32 (3.33)	8.38 (3.20)	6.23 (3.64)
Acquisition size (AS)	5.64 (3.19)	5.19 (3.49)	3.00 (2.69)
Acquisition efficiency (AE)	0.95 (1.27)	0.45 (0.42)	0.20 (0.18)

DISCUSSION

Although touchscreen devices are prevalent in children's lives and influence children's development (Cristia and Seidl, 2015; Bedford et al., 2016), there are few studies examining the effects of touchscreen on children's cognition and learning. In the present study, we used a pre- and post-test paradigm to examine whether using a touchscreen iPad could facilitate young children's learning to tell time, and whether they could transfer this learning from iPad to different media (i.e., a physical object and paper). The results showed that the post-test score was higher than pre-test after children used an iPad touchscreen app to learn how to read time on a clock. This result is consistent with our hypothesis, indicating that 5- to 6-year-old children could benefit from touchscreen technology to learn this skill. Additionally,

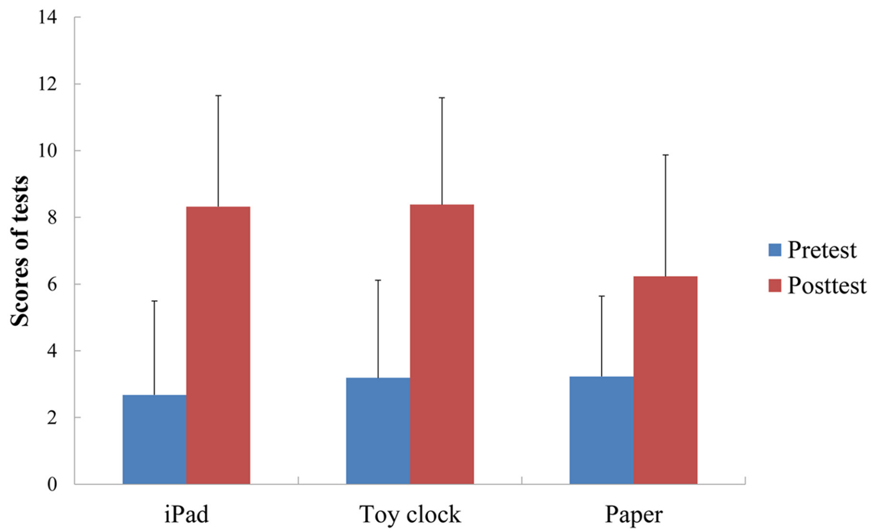

FIGURE 3 | Means of pre-test and post-test scores (with *SD*) as a function of test medium.

we found that 5- to 6-year-old children's new knowledge about telling time transferred very well from iPad to iPad and from iPad to the physical toy clock. The findings suggest that touchscreen devices or interactive touchscreen educational apps not only facilitate young children's acquisition of knowledge and skills, but also can promote transfer of new knowledge to solve problems using different media. This study moves the research from a general focus on apps to a focus on one app in particular. Implications of this study are useful for parents and teachers, who could use touchscreen technology to encourage children's active learning.

Compared with printed books and video, one special feature of touchscreen is interactivity. Children could tap, drag, and touch the objects on the touchscreen and get a response from the objects. From the view of embodied cognition, cognitive processes are deeply rooted in the body's interactions with the world (Wilson, 2002; Shapiro, 2010). Embodied cognition provides a good framework to explain why touchscreen facilitates young children's learning. A touchscreen, such as an iPad, gives children opportunities to interact with what they are learning about, not just watch and listen. Children's engagement with touchscreen apps provides motor, visual, and acoustic information, and benefits memorization (Agostinho et al., 2015; Noorhidawati et al., 2015). In this study, children could move their finger to drag the clock's minute hand and hour hand to set the time. If they did not get the right answer, they would get a voice reply telling them to try again. These exchanges with the touchscreen device are thought to be the process that promotes children's learning.

The post-test scores indicated that children could easily transfer what they learned from the iPad touchscreen to the toy clock and paper. These results were consistent with the hypothesis. Huber et al. (2016) found that 4- to 6-year-old children could learn how to solve Tower of Hanoi on an iPad touchscreen and subsequently apply this learning to physical objects. When children actively engaged in the touchscreen learning process, learning was enhanced (Hirsh-Pasek et al., 2015). Unlike passive learning from video, the touchscreen used in this study was interactive and informative, and children were willing to engage in learning.

However, after learning with the iPad touchscreen, children in the toy clock assessment group performed as well as those assessed using the iPad. This is inconsistent with our hypothesis. The result is also inconsistent with a previous study, which found that 3-year-olds showed lower transfer from touchscreen to physical objects (Moser et al., 2015). The researchers argued that young children could encode the information from the touchscreen but could not retrieve the information on new media or environments because they lacked memory flexibility. However, the memory flexibility and the cognition of children more than 3 years old have reached a new level (Zelazo et al., 1999; Dickerson et al., 2013). In this research, we recruited 5- to 6-year-old children. They could transfer knowledge very well between different media.

Part of the reason for the transfer seen in this study is that the real toy clock was similar to the clock on the iPad app in shape and color. These similarities could benefit the learning and transfer. As for the group tested with a paper drawing, the improvement of learning was the lowest. Analysis of the simple effects of test medium type for each test session revealed that children in the iPad and toy clock test groups outperformed those in the paper test group. In addition, results from AS and AE also showed that children assessed using a paper drawing acquired the least and had the lowest efficiency. The reason might be that the post-test material on paper was printed in white and black, had a very simple shape, and was far from the learning material on the iPad touchscreen app. Therefore, these features of the paper material may hinder children's transfer. For example, studies with multimedia learning showed that the shape, color and anthropomorphism of material could affect learning performance (Um et al., 2012; Plass et al., 2014; Park et al., 2015). Bright colors and anthropomorphic shape in the iPad group and the toy clock group could facilitate learning performance. This speculation still needs to be further verified.

Several limitations of this study should be acknowledged. First, it will be important in future research to ask children to report which type of medium they liked. This will give more information to explain how the assessment format might influence transfer of learning from the touchscreen to other media. Second, all the materials should be matched with regard to color, shape and anthropomorphism, to provide a more valid test of the effects of the touchscreen *per se*. Third, our learning task was telling time, and future research should evaluate the extent to which other skills learned on touchscreen can be applied to different media. Besides telling time, a variety of apps should be examined to generalize the conclusions about the promotion of touchscreen on learning. Finally, other media types (e.g., video, TV) are still to be tested. This limited intervention showed positive outcomes. It is unclear whether more extensive use could lead to negative effects, a question that still needs empirical study.

AUTHOR CONTRIBUTIONS

FW developed the study concept. All authors contributed to the study design. FW, HX, YW, JA, and YH performed the experiment, and HX conducted the statistical analyses and interpreted the results. FW, HX, and YW were primarily responsible for writing the manuscript, with all remaining authors providing critical revisions. All authors approved the final version of the manuscript for submission.

FUNDING

This research was founded by National Natural Science Foundation of China Grant (# 31300864) and Self-Determined Research Funds of CCNU from the Colleges' Basic Research and Operation of MOE (#CCNU16A02023) to the first author FW.

ACKNOWLEDGMENT

We wish to thank the children, their parents and their kindergarten teachers for participating in this study.

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Conflict of Interest Statement: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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ORIGINAL RESEARCH
published: 16 November 2016
doi: 10.3389/fpsyg.2016.01728

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Reading Touch Screen Storybooks with Mothers Negatively Affects 7-Year-Old Readers' Comprehension but Enriches Emotional Engagement

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Touch screen storybooks turn reading into an interactive multimedia experience, with hotspot-activated animations, sound effects, and games. Positive and negative effects of reading multimedia stories have been reported, but the underlying mechanisms which explain how children's learning is affected remain uncertain. The present study examined the effect of storybook format (touch screen and print) on story comprehension, and considered how level of touch screen interactivity (high and low) and shared reading behaviors (cognitive and emotional scaffolding, emotional engagement) might contribute to comprehension. Seven-year-olds (n = 22) were observed reading one touch screen storybook and one print storybook with their mothers. Story comprehension was inferior for the touch screen storybooks compared to the print formats. Touch screen interactivity level had no significant effect on comprehension but did affect shared reading behaviors. The mother–child dyads spent less time talking about the story in the highly interactive touch screen condition, despite longer shared reading sessions because of touch screen interactions. Positive emotional engagement was greater for children and mothers in the highly interactive touch screen condition, due to additional positive emotions expressed during touch screen interactions. Negative emotional engagement was greater for children when reading and talking about the story in the highly interactive condition, and some mothers demonstrated negative emotional engagement with the touch screen activities. The less interactive touch screen storybook had little effect on shared reading behaviors, but mothers controlling behaviors were more frequent. Storybook format had no effect on the frequency of mothers' cognitive scaffolding behaviors (comprehension questions, word help). Relationships between comprehension and shared reading behaviors were examined for each storybook, and although length of the shared reading session and controlling behaviors had significant effects on comprehension, the mechanisms driving comprehension were not fully explained by the data. The potential for touch screen storybooks to contribute to cognitive overload in 7-year-old developing readers is discussed, as is the complex relationship between cognitive and emotional scaffolding behaviors, emotional engagement, and comprehension. Sample characteristics and methodological limitations are also discussed to help inform future research.

Keywords: reading comprehension, shared reading, touch screen, scaffolding, developing readers, emotional engagement

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Edited by:
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University of South Dakota, USA

Reviewed by:
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Specialty section:
This article was submitted to Developmental Psychology, a section of the journal Frontiers in Psychology

Received: 20 July 2016
Accepted: 19 October 2016
Published: 16 November 2016

Citation:
Ross KM, Pye RE and Randell J (2016) Reading Touch Screen Storybooks with Mothers Negatively Affects 7-Year-Old Readers' Comprehension but Enriches Emotional Engagement. Front. Psychol. 7:1728. doi: 10.3389/fpsyg.2016.01728

INTRODUCTION

Touch screen storybook apps for smartphone and tablet devices offer an interactive multimedia reading experience for children, with animations, music, sound effects, games, and oral narration accompanying the story text. Surveys by Common Sense Media (2013) in the US and the National Literacy Trust (Formby, 2014) in the UK report that just under a third of children have read books on touch screens, but this figure is likely to increase given the rapid growth in children's access to touch screens. Latest figures from the UK show that 73% of children had access to tablets at home in 2015, up from only 14% in 2012, with 5- to 7-year-olds experiencing the largest increase in access since 2014 (Ofcom, 2015).

The present study examined the effects of touch screen storybooks and the level of touch screen interactivity on 7-year-old children's story comprehension in shared reading contexts. The aim was to explain the comprehension effects with reference to a rich set of data and observations, including data on children's liking of the storybooks, their format preferences, and their home reading environments, and observations of general shared reading activities, cognitive and emotional scaffolding behaviors, and positive and negative emotional engagement. Seven-year-olds have been somewhat under-represented in recently published studies of the effects of touch screens on literacy development where there has been a greater focus on toddlers' and preschoolers' beginning and emergent literacy (e.g., Merchant, 2015; Kirkorian et al., 2016; Neumann, 2016). However, children's experiences with the interactive multimedia features of touch screen storybooks are particularly interesting to examine at this age because they are on the cusp of independent reading due to greater fluency and improved comprehension skills (Schwanenflugel et al., 2004), but they continue to benefit from reading with a supportive adult (Clark, 2007; Mudzielwana, 2014).

The effect of interactive multimedia features on children's story comprehension has been subject to considerable research in recent years, but rapid changes in technology have also been taking place. Much of the existing experimental literature is based on older computer technologies which lack a touch screen interface but have other interactive and multimedia features to varying degrees, including oral narration, animations, sound effects, and hotspots (albeit activated by a mouse). We use the term e-book in this paper to refer in general terms to storybooks on electronic devices (including computers, e-readers, electronic consoles), but we specify where studies used touch screen technology. One relatively recent meta-analysis by Zucker et al. (2009) found that e-books in general have small to moderate effects on comprehension outcomes, though much of the evidence was based on experimental studies of children in the pre-reading or early stages of reading. However, this meta-analysis and other recent reviews of the literature (Miller and Warschauer, 2014; Bus et al., 2015) have concluded that the effects of e-books are neither consistently positive nor negative, and more needs to be done to pull apart the effects of different interactive features, the reading context, and participant characteristics on comprehension.

The dramatization of the story through animations and sound effects is thought to have potential to enhance children's story comprehension by facilitating dual coding of verbal and non-verbal story information (Paivio, 1986, 2008). Paivio's dual coding theory postulates that non-verbal stimuli might trigger questions and inferences about the verbal stimuli, resulting in deeper understanding due to interconnections between verbal and non-verbal processing. In support of this theory, studies by Verhallen and colleagues found that animations and sound effects in narrated e-books enhanced 5-year-old children's story understanding and expressive vocabulary learning in comparison to e-books with static visuals (Verhallen et al., 2006; Verhallen and Bus, 2010). These studies were strictly controlled: the animations and sound effects were in close temporal contiguity to the story and the experimenter controlled the activation of features. When 7-year-olds were allowed to control the interactive features themselves in a study by Ricci and Beal (2002), superior comprehension of animated and narrated e-books was also found in comparison to audio books, despite the fact that some of the animations were a diversion from the main story. Another study by Smeets and Bus (2014) found that interactive animations and non-interactive animations in narrated e-books had no beneficial or detrimental effects on 4- to 5-year-olds comprehension compared to e-books with static visuals, but vocabulary learning was enhanced by interactive word definition features. Thus from these studies of children's independent reading of e-books, it appears that interactive animations and sound effects have at least no detrimental effect on comprehension of e-books and perhaps a positive effect if well-designed.

When children's comprehension of interactive animated e-books is compared to their comprehension of print books, the benefits of the e-book features are less evident. Two studies report that 4- to 6-year-old children's comprehension of e-books with interactive animations, sound effects, and oral narration was comparable to their comprehension of printed books read by an adult experimenter (De Jong and Bus, 2004; Korat and Shamir, 2007). However, when interactive animations and games had low congruence with the story, children's attention was diverted from story content toward the interactive features, resulting in less complete story retellings than for print stories read by an adult (De Jong and Bus, 2002). The interactive features of e-books could be cognitively overloading young readers when they read independently. According to cognitive load theory (Sweller, 2005), multimedia features may cause children to switch between processing the story text and processing other information. This switching may exceed their processing capacity and result in cognitive overload, with detrimental effects on learning. Young children may be particularly prone to cognitive overload due to their immature cognitive and attentional skills (Courage et al., 2015).

In everyday shared reading contexts, parents often demonstrate some degree of cognitive scaffolding to support children's reading development and comprehension skills (Bruner, 1981; Sénéchal and LeFevre, 2002). Cognitive scaffolding behaviors, such as comprehension questioning and encouraging discussion, can also be trained, for example in the dialogic reading approach first introduced by Whitehurst et al. (1988). Various studies have demonstrated that this structured, scaffolding approach to reading with children leads to benefits in storytelling (Marjanovič-Umek et al., 2012), receptive language and attention (Vally et al., 2015), and vocabulary (Niklas and Schneider, 2015). The efficacy of these behaviors at promoting language learning from printed books declines considerably as children reach 4- to 5-years-old (as evident from the meta-analysis by Mol et al., 2008), but they may still benefit children's general reading development and attitudes (Niklas and Schneider, 2013).

The nature and importance of parents' cognitive scaffolding behaviors during shared reading deserves re-examination in the context of touch screen story books. The greater complexity of interactive multimedia reading, and the potential for cognitive overload, may mean that children will continue to benefit from parental support at older ages. A potential problem, however, might be parents' perceptions of, and attitudes toward, touch screen reading. Despite parents having some concerns that animations, games, and hotspots could distract children from learning, they also seem to consider touch screen reading as being particularly suited to children's independent reading because of the support from digital pronunciation and audio narration features (Vaala and Takeuchi, 2012).

Several recent studies have examined comprehension effects in shared reading contexts, where children read with a parent or other supportive adult. A study by Krcmar and Cingel (2014) found that the touch screen format by itself (in the absence of any interactive features, animations, or sounds) adversely affected the story comprehension of 2- to 5-year-olds compared to reading print storybooks, and resulted in fewer parent and child comments and questions about story content. The limited scaffolding by parents did not explain the lower comprehension scores, but comprehension was negatively affected by talk about the book format and environment, which happened more often in the touch screen condition. Chiong et al. (2012) also found that reading books on touch screens resulted in parents and their 3- to 6-year-old children engaging in less talk about story content and more non-content talk, but comprehension was only negatively affected by reading on an interactive touch screen and not by reading on a non-interactive touch screen. Parish-Morris et al. (2013) investigated the effects of electronic console books (where interactive sounds and games were activated by button presses) when parents read with their 3- and 5-year-olds. Parents engaged in less content-related talk and more behavior-related talk compared to reading printed stories, and 3-year-olds story recall was poorer, but the effect of age on comprehension was unclear because of ceiling effects for the 5-year-olds.

Krcmar and Cingel (2014) explained pre-school children's poorer comprehension of touch screen storybooks in a shared reading context by drawing on Fisch's (2000) cognitive capacity model for learning from screens. Children are thought to have limited cognitive capacity to process the narrative of the story, so non-content related talk acts to increase the cognitive load on children and reduce the resources available to process story content. Parents do not seem to have effective strategies to ameliorate the distractions of technology during shared reading, which is understandable given that sharing e-books is still a relatively infrequent activity compared to reading print books. Children's familiarity with technology does not appear to diminish the distractions of technology in shared reading contexts; instead, children with greater experience of touch screen technology in Krcmar and Cingel's (2014) study had poorer comprehension of touch screen storybooks, perhaps because they associated the technology with playing games rather than reading. More studies are needed to understand if school-aged children, who are becoming more skilled at following the narrative of a story, are better able to cope with the distractions of technology.

Although there is evidence that parents and children engage in distracting talk when reading on touch screens, which detracts from comprehension, some studies have reported more positive findings in relation to cognitive scaffolding behaviors. Lauricella et al. (2014) found that although parents offered help with the interactive features of an e-book at the expense of word definitions, verbal interactions were otherwise very similar across formats, and format did not affect 4-year-old children's comprehension. Cognitive scaffolding seems to be particularly effective when delivered by teachers or other trained adults in the school environment as demonstrated in a study by Segal-Drori et al. (2010) in which 5- to 6-year-old children's emergent word reading skills were tested after reading interactive animated e-books and print books with an adult who was trained to support word learning. Children made greatest progress in the e-book condition suggesting that interactive features can enhance children's learning during shared reading if the adult effectively scaffolds children's processing of the verbal information, perhaps relieving some of the processing burden.

Good quality adult support seems to be important if children are to effectively comprehend storybooks with interactive multimedia features, and quality is affected by emotional scaffolding behaviors as well as the cognitive scaffolding behaviors already discussed. Parents rate the emotional dimensions of shared reading – fostering an enjoyment of books and having a close and enjoyable time with the child – as more important than cognitive stimulation and fostering of reading development (Audet et al., 2008). Positive shared reading experiences as children are learning to read also predict better reading outcomes in later life and greater interest in reading (e.g., Baker et al., 2001; Hood et al., 2008; Hume et al., 2015), and children's enjoyment and motivations to read are positively related to reading attainment (e.g., Baker and Wigfield, 1999; Wang and Guthrie, 2004; Taboada et al., 2009; Petscher, 2010; Clark and De Zoysa, 2011; McGeown et al., 2015; Clark, 2016). Given the long-reaching effects of positive shared reading experiences, it is important to examine how new reading technologies affect emotional scaffolding behaviors during shared reading. The potential tension between parents who prefer print books (Zickuhr, 2013; Rideout, 2014) and children who have more positive attitudes toward e-books (Vaala and Takeuchi, 2012) may adversely affect the emotional aspects of shared reading. Researchers are beginning to examine moment to moment emotional responses during adult reading

(Graesser et al., 2012) and multimedia learning (Chung et al., 2015) to explore interrelationships between emotion, cognition and learning, and this is a promising area for further research into children's experiences with new reading technologies.

Observational studies which consider children's and parents' positive and negative emotional engagement (as evident from emotional expressions) when they read touch screen storybooks or e-books together are hard to find, but some studies have considered general patterns of positive and negative engagement during shared reading. One small scale study found that some parents actively discouraged their 6- to- 7-year old children's attention to interactive features (McNab and Fielding-Barnsley, 2014), and such discouragement could result in negative patterns of engagement. Other studies have found that interactive features promoted positive engagement between parents and their 4-year-olds during story reading (Lauricella et al., 2014), and between children, their peers and teachers during school literacy activities (Flewitt et al., 2015). In contrast, Chiong et al. (2012) found no difference in the positive and negative engagement of parents and their 3- to 6-year-old children when reading on touch screen and in print, although the stories were relatively short. It seems likely that reading interactive multimedia storybooks will prompt both positive and negative emotions, and more research is needed to understand the implications for children's comprehension.

In the present study, we examined the effect of storybook format (touch screen or print) and touch screen interactivity (high or low) on 7-year-old children's story comprehension, liking of the story, format preferences, and shared reading behaviors (including general shared reading activities, cognitive and emotional scaffolding behaviors, and positive and negative emotional engagement). The highly interactive touch screen storybook had many hotspot-activated features, including games, animations, and sound effects, in addition to sophisticated computer-generated animations and a musical soundtrack which played automatically. The less interactive touch screen storybook had hotspot activation of sentence narration and sound effects, but only static illustrations. Story comprehension was expected to be lower for touch screen formats and lowest for the highly interactive touch screen format, based on previous research about the potentially distracting nature of incidental features such as games, and because of concerns about cognitive overload and the difficulty of task switching between games and reading.

Cognitive and emotional scaffolding behaviors and emotions were observed during shared reading with the aim of further understanding the mechanisms by which storybook format and interactivity influence comprehension. Touch screen storybooks, and the highly interactive storybook in particular, were expected to negatively affect both the time that dyads spent talking about the story and mothers' cognitive scaffolding of story comprehension by asking comprehension questions, due to the distractions from the interactive features. Despite expected negative effects on cognitive scaffolding behaviors, children were expected to like touch screen storybooks more than print storybooks and to express more positive emotion during shared reading because of their engagement with the touch screen features. The effects of format and interactivity on mothers' emotional scaffolding behaviors and emotions were expected to be less straightforward because the interactive features might provoke both enjoyment and tensions between the dyads as the focus shifted between the story, hotspot activation and (in the highly interactive story) games; hence, no directional hypotheses were made.

Children's general reading abilities and the home reading environment were also examined to provide further context for the interpretation of the results; for example, poorer readers might be expected to require greater supportive behaviors from parents than better readers, and differences in access to touch screens could explain differences in comprehension.

MATERIALS AND METHODS

Participants

Participants were recruited through adverts placed in *Primary Times* magazine in the South East of England (Hampshire and Berkshire editions) in July 2015. Twenty-seven mother–child dyads participated in the study, but data from five dyads was removed due to failing to finish reading a story ($n = 2$) and incomplete video recordings ($n = 3$), leaving a final sample of 22 dyads. Child participants (14 females, 8 males) ranged in age from 6 years 4 months to 7 years 10 months (mean age = 7 years 1 month, $SD = 6$ months). Mothers ranged in age from 25 to 46 years (mean age = 37, $SD = 6$). Education levels of mothers varied: high school ($n = 7$), Bachelor's ($n = 12$), Masters ($n = 1$) and Doctoral ($n = 2$).

Materials and Measures

Reading Abilities

Children's reading abilities were assessed with the York Assessment of Reading Comprehension: Passage Reading Primary (YARC Primary; Snowling et al., 2009); a standardized measure of reading across three dimensions - reading rate, accuracy and comprehension – and normed to a UK sample. Children first completed the Single-Word Reading Test (SWRT) as a measure of their decoding ability, and the SWRT score was used to determine their starting level on the YARC passage reading task. Children were timed as they read aloud two YARC passages with errors corrected and counted by the assessor.

Questionnaires

Children's home reading environment was assessed using the Reading Environment Questionnaire (Powell and Chesson, unpublished). The first part of the questionnaire consisted of seven items to assess literacy at home, including the number of children's print and electronic books at home and the frequency of children's reading activities (rated on a 5-point scale: 1 = never, 2 = seldom, 3 = sometimes, 4 = often, 5 = very often). The second part of the questionnaire consisted of five items to assess home activities in general. Of relevance to this study was the number of hours in a typical day spent engaging in games and learning activities on electronic devices (rated on a 5-point scale: 0, 1, 2, 3, 4+ h) and the number of electronic devices that children had access to at home.

Children's liking of each storybook was recorded immediately after reading on a 4-point scale (1 = not at all, 2 = not much, 3 = a little, 4 = a lot). At the end of the second visit, children were asked if they preferred to read storybooks on electronic devices or in print.

Storybooks

Two storybooks were selected for the study: *The Prince's Bedtime* (TPB; Oppenheim, 2006) and *The Fantastic Flying Books of Mr. Morris Lessmore* (ML; Joyce, 2012). The storybooks were chosen because they matched our key criteria: available in both print and touch screen formats; not best-sellers and therefore unlikely to have been read by participants previously; suitable for 7-year-old children; and the touch screen formats of these two books varied in level of interactivity.

The two storybooks were comparable in the number of words (TPB = 732, ML = 729), the number of unique words (TPB = 329, ML = 294), and the mean number of letters per word (TPB = 5.04, ML = 5.24). Comparison was made to a small selection of graded Oxford Owls storybooks (levels 7–11) designed for the target age range, and the chosen storybooks were broadly comparable to this sample on word measures. The touch screen versions of the storybooks were available on the iOS platform: TPB was available through the Me Books app (2015), and ML was a standalone app published by Moonbot Studios (2012). None of the children in the study had previously read the storybooks in print or touch screen format.

The touch screen format of ML had a high level of interactivity, with hotspot activation of animations and story-relevant sound effects (1–12 hotspots per page) and five interactive games (up to 43 hotspots per game). The five games stepped out of the ML story to a degree and involved: writing in a blank book; completing a jigsaw; playing a tune on a piano; moving letters to create words and photographing the created words; and controlling the character's flight through movement of the iPad. Hotspot activation was prompted to some extent because the page-turning icon did not appear until some hotspots had been activated, and occasionally animations drew attention to the hotspots. ML also featured computer generated animations (mostly congruent with the story) and music which played automatically on most pages without any hotspot activation. There was an option for continuous narration (not activated by hotspots) but this feature was turned off for this study because it was not suited to a shared reading context where mothers are supporting children's developing reading skills.

The touch screen format of TPB had a low level of interactivity compared to ML, with hotspot activation of sentence narration, story-relevant sound effects, and character speech which expanded on the story (2–11 hotspots per page), but no hotspot- activated animations or games. Hotspot activation was not prompted in any way in TPB, and the digital pages could be turned even if no hotspots had been activated. All illustrations in TPB were static, and there was no background music.

Story Comprehension Questions

Children's comprehension of each story was assessed with nineteen questions in chronological order written in the following styles: picture (x4), multiple choice (x3), short-answer (x3), true/false (x5) and cloze (x4; the child completes a sentence with the final missing word). These questions were piloted in a local primary school with 6- to 7-year-old children (n = 19) to ensure that the questions for each story were matched for difficulty. The answers to comprehension questions were scored as correct or incorrect, and correct answers were totaled to give a comprehension score for each story.

Design

The storybooks and related reading comprehension questions were delivered in a 2 × 2 design (story – TPB or ML; and format – print or touch screen) and counterbalanced across participants so that each child read one story in one of the formats and the other story in the other format. Thus, each child participated in one of the TPB conditions – TPB print or TPB touch screen low interactivity [TPB TS(LI)] – and one of the ML conditions – ML print or ML touch screen high interactivity [ML TS (HI)]. There were 11 children per condition.

Procedure

Participants were visited in their home by a researcher on two occasions within a 2-week period (mean time between visits = 5 days). At the beginning of the first visit, each child's reading rate, reading accuracy, and comprehension skills were assessed using the YARC. After the YARC, each child read a story with their mother, followed by questions about liking of the storybook and story comprehension. Mothers completed the reading environment questionnaire between visits. At the second visit, each child read a second story with their mother, followed by questions about liking of the storybook, format preference, and story comprehension.

Each child read one of the stories on an iPad (provided by the researcher) and one story in print format, in counterbalanced order. Children were asked to read the story aloud and mothers were asked to listen and to offer help where necessary, as if they were supporting their child to read a story brought home from school for the purposes of home learning. Basic guidance was given on how to turn pages in the touch screen storybooks, where required, but no other instructions were given about the interactive features.

Shared reading sessions were recorded using a Panasonic HDC-SD41 High Definition Video Camera placed on a tripod in front of the dyad. The researcher left the room while the stories were being read to avoid being a distracting presence. Observations and data collection ceased when the mother or researcher noted that the child was unduly tired or distressed by the reading activity (two participants whose data was later removed from the study).

Ethical approval for the study was granted by the Ethics Committee at the University of Winchester. Mothers gave written informed consent for their own and their child's participation and they were fully debriefed at the end of the study. Children were

TABLE 1 | The observational coding scheme.

Codes	Definition
Shared reading activity	
Read	Mother or child read the story while the other listens; includes short pauses while turning pages or while appearing to silently read
Story talk	Mother or child talk about the story, including the meanings of words, the characters, the pictures, the plot, and thoughts and feelings about the story
Touch screen	Mother or child talk about, touch, or look at animations, hotspot activated features, or games; swiping to turn pages, without any disruption to the reading activity, is not included
Cognitive and emotional scaffolding	
Comprehension	Mother asks a comprehension question about the story, including the characters, the pictures, the plot
Words	Mother helps with the pronunciation or meaning of a word
Technical	Mother offers specific verbal instructions or guidance to help the child with the touchscreen activities (including turning the pages), e.g., "press this," "if you do this, that happens"
Praise	Mother praises the child in relation to the shared reading activity, including touchscreen use, e.g., "Well done," "Excellent," "You worked that out!"
Control	Mother attempts to exert control over the child's activity and uses command words, e.g., "Stop doing that," "Move on now," "Hurry up." We classed control as emotional scaffolding because of the negative emotional tone, despite mothers' positive intention to redirect children's attention back toward the story.
Child emotion; Mother emotion	
Positive	Positive facial expressions of smiling, laughter, or surprise are displayed in response to the reading task
Neutral	Calm and attentive to the reading task
Negative	Negative facial expressions of boredom, frustration, confusion, anger, or anxiety are displayed in response to the reading task

also verbally informed about the study and verbally consented to take part.

The Observational Coding Schemes

Four coding schemes were created for the study: shared reading activity, mothers' cognitive and emotional scaffolding behaviors, child emotion and mother emotion. A summary of the main codes and their definitions is provided in **Table 1**. Event durations were recorded for the shared reading activities and for the child and mother emotion coding schemes. In addition to the main codes, these coding schemes also had codes for *other* (activities or behaviors which did not fit into the main codes) and *obscured* (when poor visibility or audibility made it difficult to decide what was happening), though in practice these were rarely used (less than 0.5% of observed seconds). These coding schemes were mutually exclusive and exhaustive, meaning that each moment in the entire shared reading session was coded. Event frequency was recorded for mothers' cognitive and emotional scaffolding behaviors (nominal duration of 1 s per event). This coding scheme was mutually exclusive but not exhaustive, since only events relevant to the coding scheme were coded.

The coding schemes were piloted on a small sample of the videos by the first author (KR) and the other coders before being finalized. KR coded the shared reading activities coding scheme and trained the four other coders to use the other coding schemes (SS coded child emotion, RR coded mother emotion, HG and SH coded scaffolding behaviors). Videos were viewed in Windows Media Player and coding began when the dyads started to read or talk about the story (including the front cover) or engage in the touch screen activities. Coding finished when the dyads stopped reading or talking about the story or engaging in any touch screen activities. Coders recorded code onset times and the final offset time in Microsoft Word before the data was transferred to the GSEQ software program (General Sequential Querier; Bakeman and Quera, 2011) for analysis.

Inter-observer reliability was tested by second coding the videos for 4 of the 22 participants, which accounted for 16% of the total observation time. The second author (RP) was the second coder for the shared reading activities coding scheme and KR was second coder for the other coding schemes. Two measures of reliability were calculated in GSEQ, in line with Bakeman and Quera's (2011) recommendations: time-unit kappa with tolerance (± 2 s), which measures the length of agreements and disagreements; and event alignment kappa, which measures agreement about the onset of events (tolerance 5 s, overlap 80%). GSEQ computed the value of each time-unit kappa twice, once with each observer as the first observer.

The inter-observer reliability results are summarized in **Table 2**. Reliability was good to excellent for all coding schemes: time-unit kappas ranged from 0.83 to 0.96, event alignment kappas ranged from 0.71 to 0.85.

Statistical Analysis

Data were checked for normality using the Shapiro–Wilk test and by inspection of the skewness and kurtosis values and histograms. The YARC and story comprehension scores approximated normal distributions; therefore, this data was analyzed with parametric statistical tests. The liking and observational data deviated from normality; therefore, this data was analyzed with non-parametric Mann–Whitney U tests, with comparisons made between formats for each of the two storybooks in turn. Two-tailed significance values are reported, unless otherwise stated. Spearman's correlations were used to examine the relationships between the story comprehension data and the liking and observational data because of the non-parametric nature of some of the data. The alpha level was 0.05 for all statistical tests.

RESULTS

Children's Reading Abilities

The mean reading abilities of the child participants, as measured by the YARC, were above average: mean standard score for reading accuracy = 120.32 ($SD = 9.04$), mean standard score for

TABLE 2 | Inter-observer reliability scores for the observational coding schemes.

	Time-unit kappa, with tolerance (±2 s)	Time-unit agreement	Event alignment kappa with tolerance (5 s, 80% agreement)	Event agreement
Shared reading activity	0.94–0.95	98–98%	0.85	90%
Child emotion	0.89–0.96	99–100%	0.84	91%
Mother emotion	0.86–0.87	98–98%	0.83	90%
Mother scaffolding	0.83–0.86	99–99%	0.71	82%

Time-unit kappa is calculated twice, once with each observer entered first.

reading rate = 114.23 (SD = 11.41), mean standard score for comprehension = 111.91 (SD = 7.98). The overall mean YARC score ranged from 99.67 to 127.67 (mean = 115.48, SD = 7.78) meaning that all children were within the average to above average range. The mean number of words read correctly in the SWRT was 37.95, SD = 10.03.

Correlations between YARC and SWRT scores and comprehension scores were examined by story (**Table 3**) and by format (**Table 4**). TPB comprehension was positively correlated with SWRT and most of the YARC scores ($ps < 0.01$), with the exception of YARC rate, but ML comprehension did not significantly correlate with the YARC and SWRT scores. Comprehension of print storybooks positively correlated with SWRT and most of the YARC scores ($ps < 0.05$), with the exception of YARC rate. Comprehension of touch screen storybooks positively correlated with YARC accuracy ($p = 0.03$), but not with the other YARC and SWRT scores.

Reading Environment

Mothers estimated that there were 61–80 children's print books in the house on average, with no reports of fewer than 20 print books. Availability of children's e-books was more limited with 12 mothers reporting none and 10 reporting between 1 and 20. Mothers reported reading print books to their child significantly more often than they read books on electronic devices ($t(21) = 14.77$, $p < 0.001$); with paper books 'often' read (mean = 3.9), and e-books 'never' or 'seldom' read (mean = 1.27). Similarly, children independently read print books significantly more often (mean = 4.3) than e-books (mean = 1.6; $t(21) = 8.81$, $p < 0.001$).

Mothers reported that children spent less than an hour per day on computer games (mean = 0.41 h, SD = 0.6) and learning activities on electronic devices (mean = 0.55 h, SD = 0.6). There was an average of 6.9 electronic devices (e.g., laptops, PCs, smartphones) in the home, of which 2.6 on average were available for children to use.

Correlations between reading environment and story comprehension were examined. Since no predictions were made about how the reading environment would affect comprehension of print and touch screen story books, correlations were corrected using stepwise Bonferroni corrections. Only two relationships were significant: a negative relationship between the frequency of independent reading of books on electronic devices and comprehension of the touch screen storybooks ($r = -0.546$, $p = 0.009$), and a positive relationship between the frequency of reading print books independently and comprehension of printed books ($r = 0.534$, $p = 0.01$).

TABLE 3 | Intercorrelations between reading ability scores and story comprehension for ML and TBP storybooks (n = 22).

	2	3	4	5	6
1. ML comprehension	0.360	0.183	0.284	0.299	0.328
2. TPB comprehension		0.659**	0.395	0.549**	0.602**
3. YARC accuracy			0.505*	0.514*	0.756*
4. YARC rate				0.504*	0.636**
5. YARC comprehension					0.409
6. SWRT					

$^*p < 0.05$, $^{**}p < 0.01$.

TABLE 4 | Intercorrelations between reading ability scores and storybook comprehension in print and touch screen formats (n = 22).

	2	3	4	5	6
1. Print comprehension	0.337	0.433*	0.414	0.439*	0.631**
2. Touch screen comprehension		0.462*	0.234	0.329	0.316
3. YARC accuracy			0.505*	0.514*	0.756**
4. YARC rate				0.504*	0.636**
5. YARC comprehension					0.409
6. SWRT					

$^*p < 0.05$, $^{**}p < 0.01$.

Story Comprehension

The effects of story and format on story comprehension were examined with an ANOVA. There was a significant main effect of story, $F(1,20) = 5.076$, $p = 0.036$, $\eta_p^2 = 0.202$, with higher comprehension scores for ML (mean = 12.82, SD = 3.34) than TPB (mean = 11.96, SD = 2.52). There was also a significant main effect of format, $F(1,20) = 7.31$, $p = 0.014$, $\eta_p^2 = 0.268$, with comprehension scores higher for the print formats (mean = 13.27, SD = 1.95) than for the touch screen formats (mean = 12.82, SD = 1.99).

Story comprehension was expected to be lowest in the ML TS(HI) condition, due to the high interactivity and the presence of games that were incidental to the story, but there was no significant interaction between story and format, $F(1,20) = 0.43$, $p = 0.52$, $\eta_p^2 = 0.021$. *Post hoc* tests showed no difference in comprehension scores between ML print (mean = 14.27, SD = 1.62) and ML TS(HI) (mean = 12.90, SD = 1.97),

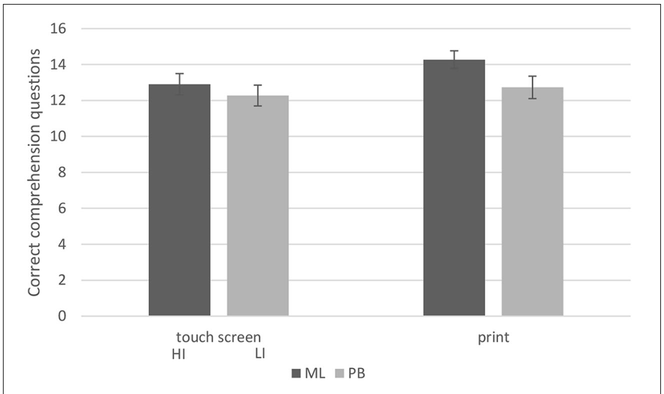

FIGURE 1 | Mean story comprehension accuracy (+SE) for ML and TPB stories, in print and touch screen format. HI, high interactivity. LI, low interactivity.

$t(20) = 1.773$, $p = 0.092$, nor between TPB print (mean = 12.73, SD = 2.05) and TPB TS(LI) (mean = 12.27, SD = 1.85), $t(20) = 0.546$, $p = 0.591$. See **Figure 1**.

Children's Liking of Stories and Format Preference

We hypothesized that children would like the touch screen storybooks more than the print storybooks but this hypothesis was not supported. Children's median liking scores were 4 ("a lot") for ML print and TPB print and 3 ("a little") for ML TS(HI) and TPB TS(LI), but there was no significant difference in liking by format for the ML storybook ($U = 43.00$, $p = 0.787$, one-tailed) or the TPB storybook ($U = 48.00$, $p = 0.781$, one-tailed).

Correlations between reported liking and comprehension were examined by story and by format. There was a significant correlation between liking of TPB and comprehension of TPB ($\rho = 0.447$, $p = 0.037$), but no significant correlation between liking of ML and comprehension of ML ($\rho = 0.381$, $p = 0.088$). Liking scores for each format did not significantly correlate with comprehension of stories in the same format (touch screen: $\rho = 0.353$, $p = 0.116$; print: $\rho = 0.261$, $p = 0.240$).

When children were asked to state their preferred format for storybook reading after they had read both formats, the majority indicated no preference ($n = 17$), four preferred print books, and one child expressed a preference for reading on a touch screen tablet.

Observations of the Shared Reading Experience

Children and mothers were video-recorded as they read two stories with their mothers over two sessions which resulted in 731 min of observations (mean per dyad = 33.24 min, $SD = 13.59$). Children read the majority of each story aloud while mothers helped with difficult words and phrases, and occasionally mothers took turns reading alternate pages when children were becoming tired. A team of coders analyzed the observations for the duration of different types of shared reading activities, the duration of children and mothers' positive and negative emotions, and the frequency of mothers' cognitive and emotional scaffolding behaviors.

Shared Reading Activities

The time spent engaging in three different shared reading activities – reading, talking about the story, and touch screen interaction – is summarized by format for each storybook in **Table 5**.

We hypothesized that touch screen reading would negatively affect the time spent talking about the story compared to reading the print format, particularly where there was high touch screen interactivity. This hypothesis was partially supported because time spent talking about the story was lower for ML TS(HI) than ML print ($U = 32.00$, $p = 0.033$, one-tailed), but there was no difference in time spent talking about the story between TPB TS(LI) and TPB print ($U = 52.00$, $p = 0.303$, one-tailed).

The dyads spend considerably longer interacting with touch screen activities in the ML TS(HI) condition (median = 8.28 min) than in the TPB TS(LI) condition (median = 0.37 min; $U = 5.00$, $p < 0.001$). This meant that the overall length of the shared reading session was significantly longer for ML TS(HI) than ML print ($U = 20.00$, $p = 0.008$), but there was no difference between the TPB formats ($U = 58.00$, $p = 0.870$). For both storybooks, the time spent reading the story did not differ by storybook format (Us > 47.00, ps > 0.375).

Cognitive and Emotional Scaffolding Behaviors

The frequencies of mothers' cognitive scaffolding behaviors (comprehension questions, word help, technical help)

TABLE 5 | Median durations (minutes) of shared reading activities for touch screen and print formats of two storybooks.

	ML Storybook			TPB Storybook		
	Print	TS(HI)	Significance	Print	TS(LI)	Significance
Read	8.80	8.22	ns	10.77	8.43	ns
Story talk	2.32	1.22	*	2.37	1.98	ns
Touch screen activity		8.28			0.37	
Overall duration	11.67	19.73	**	12.27	12.98	ns

*ML, The Fantastic Flying Books of Mr. Morris Lessmore. TPB, The Prince's Bedtime. TS(HI), touch screen with high interactivity. TS(LI), touch screen with low interactivity. Significance is based on Mann–Whitney U tests. ns, not significant, *p < 0.05, **p < 0.01.*

and emotional scaffolding behaviors (praise, control) were observed throughout the shared reading sessions. The median frequencies of scaffolding behaviors are summarized by storybook format in **Table 6**. For praise and control, median frequencies are also summarized by type of shared reading activity (either reading or story talk combined or touch screen activities). This was not relevant for the cognitive scaffolding behaviors because the nature of the coding scheme meant that nearly all of the observations of comprehension questions and word help occurred when the dyads were reading and talking about the story and all of the technical help occurred during touch screen activities. Where the medians are low (0–2), further descriptive data is provided to aid the interpretation of the significant results below. We hypothesized that the touch screen format would negatively affect the frequency of comprehension questions, but no other hypotheses were made for the effect of format on scaffolding behaviors.

Cognitive Scaffolding

There was no evidence to support the hypothesis that the frequency of comprehension questions was negatively affected by the touch screen format, because there were no significant differences in frequency by format for either storybook (Us > 53.00, ps > 0.143, one-tailed). The frequency of word help did not differ significantly by storybook format for either storybook (Us > 55.00, ps > 0.718). Technical help with touch screen features was observed significantly more often in the ML TS(HI) condition (median = 2; 10 of 11 mothers helped 67 times) than in the TPB TS(LI) condition (median = 0; 3 of 11 mothers helped 3 times; $U = 13.00$, $p = 0.001$).

Emotional scaffolding

Praise was observed significantly more frequently in the ML TS(HI) condition (median = 1; 9 of 11 mothers praised 49 times) than in the ML print condition (median = 0; 2 of 11 mothers praised 15 times; $U = 22.50$, $p = 0.007$). This difference can be explained by a higher frequency of praise when dyads were reading and talking about the story in the ML TS(HI) condition (median = 1; 8 of 11 mothers praised 35 times) compared to the ML print condition (median = 0; 2 of 11 mothers praised 14 times; $U = 29.50$, $p = 0.025$), and also by praise during touch screen activities in the ML TS(HI) condition (median = 0; 5 of 11 mothers praised 11 times; frequency was significantly greater than zero, $U = 33.00$, $p = 0.0014$). For the TPB storybook, there was no significant difference in the frequency of praise by format, either overall or when looking at different types of shared reading activities (Us > 47.00, ps > 0.363).

Control was observed relatively infrequently but was more frequent during the overall shared reading session for the TPB TS(LI) condition (median = 1; 7 of 11 mothers displayed 35 controlling behaviors) than for the TPB print condition (median = 0; two mothers displayed three controlling behaviors; $U = 32.00$, $p = 0.034$). No significant difference by format was found for times when the dyads were reading and talking about the story ($U = 44.00$, $p = 0.188$), and the frequency of control was not significantly greater than zero during TPB touch screen activities (Mann–Whitney $U = 44.00$, $p = 0.069$). For the ML storybook, there was no significant difference in the frequency of control by format for the overall shared reading session ($U = 56.50$, $p = 0.0785$), but for times when the dyads were reading and talking about the story, there were significantly fewer controlling behaviors in the ML TS(HI) condition (median = 0; 1 of 11 mothers displayed two controlling behaviors) than in the ML print condition (median = 1; 7 of 11 mothers

TABLE 6 | Median frequencies of mothers' cognitive and emotional scaffolding behaviors during shared reading activities for touch screen and print formats of two storybooks.

	ML Storybook			TPB Storybook		
	Print	**TS(HI)**	**Significance**	**Print**	**TS(LI)**	**Significance**
Cognitive scaffolding						
Comprehension	6	3	ns	2	2	ns
Words	12	15	ns	14	15	ns
Technical		2			0	
Emotional scaffolding						
Praise						
Read/Story talk	0	1	*	2	1	ns
Touch screen activity		0	*†		0	ns†
Overall frequency	0	2	**	2	1	ns
Control						
Read/Story talk	1	0	*	0	0	ns
Touch screen activity		1	**†		0	ns†
Overall frequency	1	2	ns	0	1	*

*ML, The Fantastic Flying Books of Mr. Morris Lessmore. TPB, The Prince's Bedtime. TS(HI), touch screen with high interactivity. TS(LI), touch screen with low interactivity. Significance is based on Mann–Whitney U tests. ns, not significant, *p < 0.05, **p < 0.01. †The frequency of scaffolding behaviors during touch screen activities is compared to zero.*

displayed 17 controlling behaviors; $U = 28.00$, $p = 0.013$). The frequency of controlling behaviors during ML touch screen activities was significantly greater than zero (median = 1; 7 of 11 mothers displayed 13 controlling behaviors; $U = 22.00$, $p = 0.002$).

Child and Mother Emotion

The duration of children's positive and negative emotions were coded for the overall shared reading session and were also examined by type of shared reading activity (reading and talking about the story combined or touch screen activities). The median durations of children's and mothers' positive and negative emotions and the relative duration of these emotions (as a percentage of total observation time) are summarized in **Table 7**. It was important to determine if story format affected the total duration of emotions during the shared reading sessions, but the effect of story format on length of the shared reading session also had to be considered; hence, relative durations were also analyzed. We hypothesized that the touch screen storybooks would positively affect the duration of children's positive emotions, but we made no hypotheses about the effects on children's negative emotions or mothers' emotions.

Child positive emotion

For the ML storybook shared reading sessions, children expressed positive emotions for a significantly longer total duration in the ML TS(HI) condition (median = 68 s) than in the ML print condition (median = 10 s; $U = 22.00$, $p = 0.005$, one-tailed), supporting the hypothesis that touch screen storybooks would positively affect children's positive emotions. There was a marginally significant difference by format in the relative duration of children's positive emotions for the ML storybook, with relative duration directionally greater in the ML TS(HI) condition (median = 5.76%) than in the ML print condition (median = 1.68%; $U = 35.00$, $p = 0.051$, one-tailed). The differences by format can be explained by the positive emotions expressed by children during the touch screen activities of the ML TS(HI) condition (median = 48 s; duration significantly greater than zero, $U = 5.50$, $p < 0.001$). When the dyads were reading and talking about the story, there was no significant difference between the ML TS(HI) and ML print conditions ($U = 56.00$, $p = 0.767$) in the duration of positive emotions.

For the TPB storybook shared reading sessions, there was no significant difference in the duration of children's positive emotions between the TPB TS(LI) condition and the TPB print condition ($U = 54.50$, $p = 0.651$, one-tailed). Directionally, the difference was opposite to the hypothesized effect of touch screen storybooks, with the duration of positive emotions lower for the TPB TS(LI) condition (median = 26 s) than for the TPB print condition (median = 43 s). The relative duration of children's positive emotions did not differ significantly between the TPB TS(LI) condition and the TPB print condition ($U = 53.50$,

TABLE 7 | Median duration (seconds) and median relative duration (% of observed time) of children's and mothers' emotions during shared reading activities for touch screen and print formats of two storybooks.

	ML storybook			TPB storybook		
	Print	**TS (HI)**	**Significance**	**Print**	**TS(LI)**	**Significance**
Child positive emotion						
Read/Story talk	10	19	ns	43	15	ns
Touch screen activity		48	***†		0	*†
Overall duration	10	68	**	43	26	ns
Overall relative duration	1.68%	5.76%	ns	5.83%	4.11%	*ns*
Child negative emotion						
Read/Story talk	0	1	*	2	0	ns
Touch screen activity		0	ns†		0	ns†
Overall duration	0	1	*	2	0	ns
Overall relative duration	0.00%	0.10%	*	0.23%	0.00%	ns
Mother positive emotion						
Read/Story talk	34	26	ns	103	30	*
Touch screen activity		123	***†		0	*†
Overall duration	34	189	*	103	36	ns
Overall relative duration	5.55%	12.41%	ns	9.35%	6.00%	ns
Mother negative emotion						
Read/Story talk	0	0	ns	0	0	ns
Touch screen activity		0	*†		0	ns†
Overall duration	0	2	ns	0	0	ns
Overall relative duration	0.00%	0.14%	ns	0.00%	0.00%	*ns*

*ML, The Fantastic Flying Books of Mr. Morris Lessmore. TPB, The Prince's Bedtime. TS(HI), touch screen with high interactivity. TS(LI), touch screen with low interactivity. Significance is based on Mann–Whitney U tests. ns, not significant, *$p < 0.05$, **$p < 0.01$, ***$p < 0.001$. †The duration of emotions during touch screen activities is compared to zero.*

$p = 0.674$, one-tailed), though the relative duration was shorter for the TPB TS(LI) condition (median = 4.11%) than for the TPB print condition (median = 5.83%). When the dyads were reading and talking about the story, there was no significant difference by TPB storybook format in the duration of children's positive emotions ($U = 42.50$, $p = 0.236$), but the duration of children's positive emotions was significantly greater than zero during TPB touch screen activities (median = 0; 5 of 11 children expressed positive emotion for 250 s; $U = 33.00$, $p = 0.014$).

Child negative emotion

Children expressed negative emotions for relatively brief durations, and some did not express any negative emotions at all ($n = 13$). Median durations ranged from 0 to 2 s, so further descriptive data is provided below to aid interpretation of the significant results.

For the ML storybook shared reading sessions, children expressed negative emotion for significantly longer in the ML TS(HI) condition (6 of 11 children expressed 85 s of negative emotion) than in ML print condition (1 of 11 children expressed 2 s of negative emotion; $U = 34.00$, $p = 0.035$). The relative duration of children's negative emotion was also greater in the ML TS(HI) condition (median = 0.1%) than in the ML print condition (median = 0.0%; $U = 34.50$, $p = 0.035$). The difference between conditions was driven by a significantly longer duration of negative emotion when reading and talking about the story in the ML TS(HI) condition (6 of 11 children expressed 70 s of negative emotion) than in the ML print condition (1 of 11 children expressed 2 s of negative emotion; $U = 32.00$, $p = 0.023$). The duration of children's negative emotions during touch screen activities in the ML TS(HI) condition was not significantly greater than zero ($U = 49.50$, $p = 0.148$).

For the TPB storybook shared reading sessions, the duration of children's negative emotions did not differ significantly between the TPB TS(LI) condition and the TPB print condition ($U = 37.50$, $p = 0.080$), though directionally the duration of negative emotions was shorter for the TPB TS(LI) condition (2 of 11 children expressed 52s of negative emotion) than the TPB print condition (6 of 11 children expressed 127 s of negative emotions). There was no significant difference in the relative duration of children's negative emotions between the TPB TS(LI) condition and the TPB print condition ($U = 37.50$, $p = 0.080$). When considering only the times when the dyads were reading and talking about the story, there was no significant difference between the TPB conditions ($U = 37.50$, $p = 0.080$), nor was the duration of children's negative emotions during TPB touch screen activities significantly greater than zero ($U = 60.50$, $p = 1.00$).

Mother positive emotion

During the ML storybook shared reading sessions, mothers expressed positive emotions for significantly longer durations in the ML TS(HI) condition (median = 189 s) than in the ML print condition (median = 34 s; $U = 29.00$, $p = 0.039$). When the relative duration of mothers' positive emotions was examined, it was directionally greater for the ML TS(HI) condition (median = 6% of observation time) compared to the print condition (median = 2%), but the difference was not significant ($U = 34.50$, $p = 0.086$). The difference in duration between the two ML conditions can be explained by the positive emotions expressed by mothers during the touch screen activities of the ML TS(HI) condition (median = 123 s; duration significantly greater than zero; U = 0, p < 0.001). When the dyads were reading and talking about the story, there was no significant difference between the two ML conditions in the duration of mothers' positive emotions ($U = 55.00$, $p = 0.718$).

During the TPB storybook shared reading sessions, the duration of mothers' positive emotions did not differ significantly by condition ($U = 38.50$, $p = 0.148$), nor did relative duration ($U = 53.50$, $p = 0.643$). When dyads were reading and talking about the story, mothers expressed positive emotions for significantly shorter durations in the TPB TS(LI) condition (median = 30 s) than in the TPB print condition (median = 103 s; $U = 28.50$, $p = 0.036$). The duration of mothers' positive emotions during TPB touch screen activities was significantly greater than zero seconds (median = 0; 4 of 11 mothers displayed positive emotions for 264 s; $U = 38.50$, $p = 0.032$).

Mother negative emotion

Mothers expressed negative emotions for relatively brief durations, and some did not express any negative emotions at all ($n = 14$). Median durations ranged from 0 to 2 s, so further descriptive data is provided below to aid interpretation of the significant results.

For the ML storybook, there were no significant differences in the duration of mothers' negative emotion between the ML TS(HI) and ML print conditions either, overall or when the dyads were reading and talking about the story, nor was there any difference in relative duration (Us > 48.00, ps > 0.223). Mothers expressed negative emotions during the ML touch screen activities for a duration that was significantly greater than zero (five mothers for a total of 38 s; $U = 33.00$, $p = 0.014$).

For the TPB storybook, there were no significant differences between the TPB TS(LI) and TPB print conditions, either in duration or relative duration of mothers' negative emotions, nor in the duration of mothers' negative emotions when the dyads were reading and talking about the story (Us > 54.00, ps > 0.606). Mothers did not express negative emotions during the TPB touch screen activities for a duration significantly longer than zero ($U = 49.50$, $p = 0.148$).

Comprehension and Shared Reading Observations

Correlations between children's comprehension and shared reading behaviors were examined for each storybook separately, regardless of format, to further understand the different patterns observed for the two storybooks. Comprehension of the ML story (highly interactive when in touch screen format) was significantly negatively correlated with the length of the shared reading session ($\rho = -0.448$, $p = 0.036$). There was a marginal negative correlation between time taken to read the ML story (excluding time spent talking about the story and engaging with touch screen activities) and comprehension ($\rho = -0.385$, $p = 0.076$), but no other correlations were significant (ρs < −0.358, ps > 0.102). Comprehension of the TPB story (less interactive when in touch screen format) was significantly negatively correlated with the frequency of controlling behaviors of mothers ($\rho = -0.483$, $p = 0.023$). There was a marginal negative correlation between the frequency of praises and TPB comprehension ($\rho = -0.403$, $p = 0.063$), but no other correlations were significant ($\rho s < 0.320$, $ps > 0.146$).

Children's reading abilities may have affected some of the shared reading behaviors, so we examined correlations with the mean YARC scores. There were significant negative correlations between reading ability and three variables: the frequency of word help ($\rho = -0.0611$, $p = 0.003$), the frequency of mothers' controlling behaviors ($\rho = -0.499$, $p = 0.018$), and the time taken to read the story ($\rho = -0.693$, $p < 0.001$).

DISCUSSION

The present study examined the effects of reading touch screen storybooks with different levels of interactivity on 7-year-old readers' comprehension, storybook liking, format preferences and shared reading behaviors. Detailed observations of shared reading behaviors and activities were collected from 22 mother-child dyads as they read two storybooks together, one in print and one in touch screen format, with the aim of further understanding the underlying mechanisms behind any effects on comprehension. As a group, our 7-year-old participants were above-average readers, with good access to electronic devices in the home, good access to print books in the home, but limited or no access to books on electronic devices in the home.

Children's comprehension was inferior for the touch screen formats of two storybooks (when the results were pooled), which was in line with the hypothesized effect of reading format on comprehension, but there was no evidence that the level of touch screen interactivity had an effect. The level of touch screen interactivity did affect shared reading behaviors, such that the expected reduction in time spent talking about the story and the expected increase in children's positive emotional engagement was only evident for the highly interactive touch screen storybook. The highly interactive touch screen storybook had other notable effects including significantly longer shared reading sessions (due to several minutes of engagement with touch screen activities) and increased negative emotional engagement from children (alongside increased positive emotional engagement). The hypotheses that touch screen reading would negatively affect the frequency of mothers' comprehension questions and positively affect children's liking of the storybooks were not supported.

The effects of touch screen reading on mothers' emotional scaffolding behaviors and emotional engagement were expected to be complex because of tensions between 'fun' interactive features and mothers' learning orientation during shared reading. The highly interactive touch screen storybook increased mothers' positive emotional engagement and the frequency of praise, including praise during reading and talking about the story, while the less interactive touch screen storybook increased the frequency of controlling behaviors, compared to print storybooks. Touch screen storybooks did not significantly affect mothers' negative emotional engagement during the overall shared reading session, but some mothers did express negative emotions for brief though notable durations during the highly interactive touch screen activities.

Comprehension

Shared reading of touch screen storybooks resulted in inferior story comprehension compared to reading the same stories in print format, as predicted. This finding supports previous research that interactive multimedia features can interfere with children's comprehension in shared reading contexts (Chiong et al., 2012; Parish-Morris et al., 2013). However, the expected interaction between touch screen interactivity level and comprehension was not found, and when comprehension was examined for each storybook individually, neither the highly interactive nor the less interactive touch screen storybook affected children's comprehension in comparison to the print storybook. The small sample size unfortunately limited the ability of the study to detect small effects on comprehension for the individual storybooks, so there was no support for the hypothesis that highly interactive touch screen features (including games with limited story congruence) are more detrimental to comprehension than less interactive and more congruent touch screen features.

Our comprehension findings lend some support to the theory that the presence of any interactive multimedia features places greater demands on information processing compared to reading in print, and risks cognitive overload due to the need to switch between different types of tasks (Sweller, 2005; Bus et al., 2015; Courage et al., 2015). The findings offer no support to Paivio's (2008) dual-coding approach which suggests that interactive features congruent with the story would aid comprehension. The interactive sound effects, character speech and sentence narration of the less interactive touch screen storybook in our study were congruent with the story, but no positive effect on comprehension was found.

Three findings are particularly relevant to understand how processing the story plot might be affected by touch screen features: (1) the highly interactive touch screen storybook resulted in significantly longer shared reading sessions because of the touch screen interaction time; (2) the length of the shared reading session was negatively related to comprehension across both storybooks, and (3) touch screens did not affect time taken to read the story itself. These findings lead us to conclude that children's ability to process the plot as a coherent whole was being disrupted by touch screen activities interspersed between reading the story, which in turn meant that it took longer to reach the end of the story despite reading time being unaffected. It would be interesting to examine if prompting parents and children to recap the story after significant periods of touch screen interaction would ameliorate the negative effects on comprehension.

The children in our study were 7-year-old developing readers with above average reading abilities but that did not appear to protect them from the detrimental effects on comprehension which may have resulted from cognitive overload and task switching. Children in this age range have immature cognitive and attentional skills (see Courage et al., 2015, for a review) but to develop as readers they are required to constantly and accurately map multi-modal information – of a known sound (phoneme) to an unfamiliar visual code (letter or grapheme)- and to build an understanding of the text. It is also worth noting that the children in our study read aloud the majority of the each story, while mothers helped with word pronunciation, and meaning, but only read aloud occasionally. This would have significantly increased children's cognitive load compared to listening to the story being read by their mother or a narrator, as is typical in studies with younger children. Given these challenges, it is unsurprising that developing readers in shared reading contexts, however proficient in comparison to peers, are susceptible to cognitive overload and task-switching effects.

Children's home reading environment had some influence on comprehension of the storybooks in our study. As would be expected, there was a strong relationship between the frequency of reading printed books independently and the comprehension of the two storybooks in printed format, but perhaps surprisingly there was a negative relationship between the frequency of reading e-books independently and comprehension of the two storybooks in touch screen format. This effect of technology experience is similar to that reported by Krcmar and Cingel (2014), and is worthy of further exploration with a larger sample. Perhaps young children with more experience of reading interactive books pay greater attention to interactive features and games and less attention to the story. Older children (8–16 years old) have been found to make greater progress in their reading skills when they more frequently accessed e-books at school (Picton and Clark, 2015), but e-books designed for older school children do not typically feature the cutting edge multimedia animations and games that are appearing in the latest touch screen storybook apps for emergent and developing readers. As reading on interactive touch screens becomes more common, it will be important to understand how longer term exposure affects the early development of reading comprehension skills.

Cognitive Scaffolding

Shared reading of interactive touch screen storybooks did not affect mothers' cognitive scaffolding of comprehension in comparison to print storybooks, contrary to our expectation. The expected negative effect on the length of time that the dyads talked about the story was evident, though only for the highly interactive storybook. Neither cognitive scaffolding behaviors nor duration of story talk had a significant relationship with children's comprehension, despite comprehension being poorer for touch screen storybooks at an overall level.

Our cognitive scaffolding findings are similar to Chiong et al. (2012) who found both a combination of reduced talk about the story and poorer comprehension when reading touch screens. However, in contrast to Parish-Morris et al. (2013) and Krcmar and Cingel (2014) we found no significant reduction in comprehension questioning, nor did we find a significant reduction on word scaffolding as reported by Lauricella et al. (2014). Our child participants were at least 2–3 years older than the children in these previous studies, and mothers may have been less inclined to ask comprehension questions because of the more developed comprehension skills of 7-year-olds, particularly given the above average reading abilities of our sample.

Mothers' most frequent cognitive scaffolding behavior in our study was support with word pronunciation and meaning, and the frequency of this behavior was negatively related to children's reading abilities. Directive support with technical features of the touch screens was very infrequent, which could have been due to limited knowledge of touch screen features or limited interest in encouraging the use of interactive features. A motivation to support reading fluency by helping with word pronunciation and meaning may have come to the fore in all conditions of our study, because children were being observed as they read aloud. Further observations of shared reading when utilizing the oral narration function of touch screen storybooks would help to explain these observations.

While it is positive that reading on touch screens did not appear to disrupt mothers' normal scaffolding of comprehension and word pronunciation and meaning, there appears to be untapped potential for touch screen storybooks to support and enhance these behaviors. Several studies have found that mothers' cognitive scaffolding behaviors spontaneously occur at relatively low levels but can be increased by receiving training in dialogic reading skills (such as open-ended questions and plot expansions), with corresponding benefits for children's literacy and enjoyment of reading (Lonigan et al., 1999; Mol et al., 2009; LaCour et al., 2013; Beschorner and Hutchison, 2016). Touch screen story books which prompt and guide the supportive behaviors of parents during shared reading could positively impact on children's comprehension, though the effects may be more pronounced for poorer readers.

Emotional Scaffolding

Two emotional scaffolding behaviors of mothers were examined in this study. Praise had a positive emotional tone, while control had a negative emotional tone even though mothers' were attempting to scaffold attention to the story. These emotional scaffolding behaviors were differentially affected by the level of interactivity of touch screen storybooks. Praise was more frequent for the highly interactive touch screen storybook compared to print, while controlling behaviors were more frequent for the less interactive touch screen storybook compared to print.

Praise occurred more frequently during shared reading of the highly interactive touch screen storybook for two reasons: mothers were praising more than they did in the print condition when the dyads were reading and talking about the story, and they were also praising at a notable level during engagement with touch screen activities. The higher frequency of praise from mothers could be related to the relative ease with which children worked out the touch screen features of a novel and highly interactive storybook, including swiping to turn pages, hotspot activation and games, particularly as mothers typically only provided two instances of directive technical support. More frequent praise when reading and talking about the story might have been an attempt to positively encourage attention to the story in response to the distractions of technology, but we can only speculate because we did not ask mothers about their intentions. No relationship was found between praise and children's comprehension. We know of no other study which specifically examined the effect of touch screen technology on praise, but our finding is consistent with Lauricella et al. (2014) who observed greater positive engagement between parents and children when reading interactive e-books.

Controlling behaviors were more frequent during shared reading of the less interactive touch screen storybook compared to print, and controlling behaviors were also negatively related to comprehension and negatively related to reading ability. Our anecdotal observations indicated that the controlling behaviors during shared reading of the less interactive touch screen storybook were often happening when children were repeatedly playing with the swipe feature to turn the page which was a distraction from the story. There was very limited engagement with the hotspots, which often went unnoticed in the static illustrations. We suspect that mothers may have been particularly motivated to direct the attention of children who needed more help with reading away from story-irrelevant touch screen features and back toward the story, but further research is needed with a wider range of reading abilities because all of the children in our sample were average or above average readers.

It is interesting that the highly interactive touch screen storybook had no significant effect on controlling behaviors even though previous research has highlighted parental concerns about interactive features with perceived low educational value, such as games (Vaala and Takeuchi, 2012). Despite these potential concerns, there was no indication that parents were using controlling behaviors to direct attention away from the highly interactive features, at least not on the first exposure to the storybook.

Emotional scaffolding of touch screen reading deserves further research attention. Praise and control were observed at relatively low levels in our study, and it may be worth looking at a wider range of parental behaviors during shared reading which promote reading enjoyment and alleviate frustrations.

Child and Mother Emotion

Children and mothers' demonstrated greater positive emotional engagement with the highly interactive touch screen storybook than with the same story in print, due to additional positive emotions expressed during the touch screen activities. There was no difference in children and mothers' positive emotional engagement when they were reading and talking about the story, despite the highly interactive storybook having unprompted animations playing during these times. Thus, it appeared to be interactivity rather than the animations alone which prompted positive emotions. There was no significant relationship between positive emotional engagement and comprehension, which was somewhat surprising given that reported enjoyment of reading improves reading attainment outcomes (Clark and De Zoysa, 2011), but few studies have considered the relationship between observed emotions during reading and comprehension.

Children also demonstrated greater negative emotional engagement with the highly interactive touch screen storybook compared to the print storybook, particularly when they dyads were reading and talking about the story. When children were engaging in the touch screen activities, they did not express negative emotions for a notable duration. Mothers, in contrast, demonstrated some negative emotional engagement during the touch screen activities of the highly interactive storybook, though their negative emotional engagement was not affected by format at an overall level. Some caution must be applied to the interpretation of the negative emotional engagement findings because negative emotions were only expressed briefly by some children and mothers. From our anecdotal observations, we suggest that the pattern of negative emotional engagement observed for the highly interactive touch screen storybook appeared to be indicative of some tension created by switching between reading and talking about the story and engaging in the touch screen activities. Some children got frustrated during the story by a desire to skip ahead to the touch screen activities, and some mothers got frustrated when touch screen activities were too prolonged.

Future studies with larger samples, greater contextual analysis, and analysis of child and mother characteristics are needed to explore the underlying reasons for negative emotional engagement with touch screen storybooks and its effects. Experiencing negative emotions during reading is not necessarily detrimental because it could promote productive thinking and discussion (Graesser et al., 2012), thus potentially enriching engagement and enhancing learning where there is appropriate scaffolding, though there was no evidence of a relationship between negative emotions and comprehension in our study.

The less interactive storybook had no effect on children's positive and negative emotional engagement, or on mother's negative emotional engagement, perhaps because the interactive features were often missed. Mothers' positive emotional engagement was lower for the less interactive storybook than for the print format during times when the dyads were reading and talking about the story. This finding coincides with increased control by mothers when the dyads were reading and talking about the less interactive storybook, seemingly in an attempt to redirect children's attention from playing with the page-turning swipes. This focus on control could have reduced the opportunity for positive emotional engagement.

Storybook Liking and Format Preferences

Children's reported liking of the storybooks was not affected by storybook format, in contrast to our expectation and despite the observed differences in emotional engagement for the highly interactive touch screen storybook. The majority of children reported no preference for storybook format at the end of the study, which supports Jones and Brown's (2011) finding that children showed no difference in expressed preference for or liking of e-books over print books, even after repeated exposure. Reported preferences and liking may not, however, be an entirely accurate indication of behaviors because Jones and Brown (2011) also observed that children chose to read e-books more often than print books when given the choice.

Sample characteristics may have limited the variance in the liking ratings in our study: the children had above average reading abilities overall, and children who are reading at a higher level than expected for their age are more likely than poorer readers to enjoy reading in general (Clark, 2016). We did not ask mothers for their liking and preferences, which might have helped understand their observed negative emotions and controlling behaviors.

Limitations

The child and mother dyads were less confident with the use of touch screen devices than we had anticipated, and the dyads missed several of the interactive features. Hotspots were hardly noticed in the less interactive storybook unless they happened to be pressed accidentally, and although the on-screen prompts facilitated much more interaction with the highly interactive storybook, the hotspots and games were still not used to their full potential. The child participants had relatively little experience of reading books on electronic devices, despite using electronic devices for games and other learning activities. As a result, our study can draw conclusions about the effects of the relatively novel experience of shared reading of touch screen storybooks, but it does not demonstrate the effects of touch screen storybooks when interactive features are used to their full potential by experienced touch screen readers. It would be beneficial for future studies to provide parent–child dyads with greater exposure and training in the use of interactive features.

The analysis of the comprehension findings was complicated to some extent by the fact that children found one story (ML) easier to understand than the other (TPB), despite careful piloting of the comprehension questions to match them for difficulty. This could be resolved by creating materials specifically for the purposes of the study, where the story remains constant but the interactive multimedia features are varied. Nevertheless, there is value in examining shared reading in a naturalistic situation with real touch screen storybook apps, particularly as the sophistication of the content and features of stories such as *The Fantastic Flying Books of Mr. Morris Lessmore* is far beyond what could realistically be produced for academic research.

Sampling issues also restricted the ability of our study to explain the comprehension differences. There were only 22 mother-child dyads and 44 observations in total, and the characteristics of the sample were relatively narrow (good readers, well-educated mothers), which may have limited the variance needed to find small effects. Sample size does generally have to be sacrificed to some extent when conducting detailed observational analysis, but the richness of the data helps to provide direction to future research.

We did not consider the effects of direct on-screen touch on comprehension, since our observations were limited to time spent looking at and engaging with touch screen activities rather than counting the number of touches. Touch may further complicate the relationship between interactive multimedia storybooks and comprehension, and research is only beginning to explore how direct on-screen touch might influence children's learning (e.g., Walsh and Simpson, 2013; Vatavu et al., 2015; Kirkorian et al., 2016).

CONCLUSION

This study provides some indication that children's inferior comprehension of touch screen storybooks in a shared reading context could be related to the increased length of the shared reading session and reduced story talk, at least when there is high interactivity, and it could also be related to more maternal control, particularly when the interactive features are less engaging. The results were complicated by the fact that format had no effect on comprehension when considering the two storybooks individually. High touch screen interactivity enriched emotional engagement and increased maternal praise, and touch screens had no detrimental effects on comprehension questioning and word help, but there was no evidence that these observations were related to comprehension. Further research with larger samples is needed to fully examine the mechanisms driving the comprehension effects.

Interactive touch screen storybooks clearly have potential to increase positive emotional engagement during shared reading, and well-designed educational features may also help to reduce the potential negative effects of task-switching and to support refocusing of attention back to the story. Our findings highlight the potential for storybook apps to include design features which directly support the comprehension and word decoding skills of developing readers, either by prompting relevant cognitive scaffolding behaviors from parents or by acting as a substitute for skilled parental support. Further studies should examine the shared reading behaviors of children with a broader range of reading abilities, since the good readers in this study did not require a great deal of cognitive scaffolding from mothers. The effects of increased exposure and confidence with touch screen technology should also be studied, since the technology is still relatively novel in the context of storybook reading.

AUTHOR CONTRIBUTIONS

The three authors (KR, RP, JR) jointly conceived and designed the study, and each author contributed to the drafting, revision and approval of the final paper. All authors agree to be accountable for all aspects of the work. KR led the design and piloting of the observational coding scheme, analysis of the coding data, and writing of the final paper. RP led the design and piloting of the comprehension questions, participant recruitment, and analysis of the comprehension data.

FUNDING

The study was supported by funds from the University of Winchester (granted to KR, RP, and JR) and the University of Reading (granted to RP).

ACKNOWLEDGMENTS

We are grateful to the mothers and children who generously gave their time to participate in this study. We thank Rebecca

Steward-Holness for her help with participant recruitment and data collection during the placement year of her BSc Psychology degree. We also thank Hannahlee Goddard, Stephanie Harris, Rosie Robinson, and Stephanie Sharpe for assistance with video coding, and other students who have helped for short periods in the search for suitable touch screen storybooks and in the creation of comprehension questions, including Shabana Mabood, Paula Charlton, Keir Simmons, Lucy Parr, Kate Purdy, and Fiona Taylor.

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Conflict of Interest Statement: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

frontiers in Psychology

OPINION
published: 15 November 2016
doi: 10.3389/fpsyg.2016.01739

The Implementation of Bring Your Own Device (BYOD) in Primary [Elementary] Schools

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Keywords: BYOD, bring your own device, mobile technologies, BYOT

OPEN ACCESS

Edited by:
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Reviewed by:
Alexis Lauricella,
Northwestern University, USA
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Specialty section:
This article was submitted to Developmental Psychology, a section of the journal Frontiers in Psychology

Received: *15 July 2016*
Accepted: *21 October 2016*
Published: *15 November 2016*

Citation:
McLean KJ (2016) The Implementation of Bring Your Own Device (BYOD) in Primary [Elementary] Schools. Front. Psychol. 7:1739. doi: 10.3389/fpsyg.2016.01739

The increasing emphasis on one-to-one technology programs has led to schools exploring options for technology provision (Stavert, 2013). This is because of costs involved in ensuring one-to-one access to technology for all children (Cardoza and Tunks, 2014). Of interest in the current educational climate are *bring your own device* (BYOD) approaches to provision where students bring their own technology devices to school for learning. This paper considers issues around the application of BYOD approaches in primary [elementary] schools.

EDUCATIONAL CONTEXT

The introduction of mobile devices in schools has been met with approval from the education establishment. This is mainly due to the reported potential of these devices for supporting contemporary views of teaching and learning (Traxler, 2009). As examples of mobile devices, mobile phones and mobile tablet technologies have potential to support collaborative learning in conventional and online learning environments (Falloon, 2015). The instant access to, and flexibility of mobile devices are seen as enablers for collaborative learning (Murray and Olcese, 2011). It is these features of mobile technologies that have influenced a change in the way that technology use is viewed in primary education. Although most educators would agree that mobile technologies have the potential to transform teaching and learning practices in schools (Zurita and Nussbaum, 2004; Traxler, 2009; Hedberg, 2014) models to support this provision continue to be debated.

MODELS OF TECHNOLOGY PROVISION

Models for provision of technology have changed (see for example Alberta Education, 2012; Stavert, 2013) since computers were first introduced in schools. These changes can be seen through a shift from computer labs to learning pods, learning pods to notebooks programs, and notebook programs to one-to-one mobile technology programs. These shifts are largely attributed to sociocultural theoretical influences on technology provision. These influences were initially realized through shared learning and learning pod arrangements and are now evident in models for one-to-one access and collaborative use of technologies (Kearney et al., 2015).

Two main forms of provision for one-to-one ratios of student access have emerged. The first involves schools purchasing mobile devices, which remain on site as class sets. Limitations of this model include purchase costs for schools, information technology (IT) infrastructure required to maintain the devices and keeping track of student work throughout schooling (Nelson, 2012). The second form of provision involves student ownership of, and responsibility for these devices. This model requires parents to purchase self-sourced devices recommended by the school or through leasing arrangements instigated through school processes (Johnson, 2012; Bruder, 2014). This is referred to as the *Bring Your Own Device* (BYOD) or *Bring Your Own Technology* (BYOT) model. Using the BYOD model parents provide the technologies for their children's use in similar ways to other educational resources such as books (Falloon, 2015).

ARGUMENTS FOR THE IMPLEMENTATION OF BYOD IN PRIMARY SCHOOLS

The BYOD model is reported as benefiting schools through relieving the cost pressure for one-to-one technology provision (Cardoza and Tunks, 2014) and providing relief for technology support (Nelson, 2012). Several adaptions of this model have emerged to support parents in the process of purchasing mobile devices for educational use. These include parents having responsibility for (a) purchase, maintenance, and software installation; (b) purchase, but the device is managed by the school; and (c) purchase, but varying levels of maintenance and software installation are supported by the school (Sweeney, 2012).

The ubiquity of mobile devices and pervasive ownership from all socioeconomic groups provide compelling reasons for the adoption of BYOD in schools (Johnson, 2012; Stavert, 2013). Although BYOD in primary schools may draw on these elements of students' lives and provide continuity across school and home learning contexts (Lai et al., 2013) the impact of BYOD on these contexts is less certain.

Reported benefits associated with BYOD in schools include high levels of student engagement through interactive assignments, the use of a range of apps to teach core curriculum skills and independent inquiry learning opportunities (Bruder, 2014). This engagement is attributed to student-centered pedagogical approaches that have emerged in response to the non-standardized learning environments that are created when students bring their own devices to school for learning (Sweeney, 2012). Other benefits of BYOD practices in schools are reported by Song (2014). In this Hong Kong study students' perceptions of learning through participation in a BYOD science inquiry program were investigated. Although this study was limited to year 6 students in one school, the findings support claims that BYOD practices contribute to student engagement and support learning through student-centered inquiry approaches.

BYOD in schools is described as contributing to flexible and collaborative learning environments (Johnson et al., 2014). For example, Clark (2013) describes the benefits for students in US county schools of engaging in BYOD practices in terms of creativity, critical thinking, communication, collaboration, confidence, citizenship, and community. Clark (2013) argues that the implementation of BYOT practices contributed to transforming the traditional classroom through empowering teachers and students using personalized learning approaches (Clark, 2013). Similar innovative practices are described by Falloon (2015) in New Zealand research where benefits of using iPads extended into the home. Findings such as these lend support to arguments for BYOD in schools but also suggest a need to examine the broader influences of BYOD on family and school practices.

ARGUMENTS AGAINST BYOD IN PRIMARY SCHOOLS

Constraining factors influencing the implementation of BYOD in primary schools include the legal obligations of schools around the support and provision of these devices for all students (Bathon, 2013). Approaches to ensuring security and appropriate use of devices outside of school (Fogarty and Carr, 2014) include the use of guidelines to improve network management (Sweeney, 2012) and the use of filters and controls (Ullman, 2011). Despite this, the extent to which schools can control security and out of school use is unclear.

A further argument against the implementation of BYOD in primary schools' centers on equitable access to mobile devices for all children (Stager, 2011; Johnson, 2012). For example, variations in models purchased, applications installed on individual devices and subscriptions to applications with controlled access to levels. One way of addressing this issue is through a combination of BYOD and school-based models of mobile technology provision. Using these approaches schools purchase additional mobile technologies to supplement one-to-one ownership in efforts to ensure that all children have access to a device for learning (Ng and Nicholas, 2013; Song, 2014; Warschauer et al., 2014). There is some disagreement about whether these approaches contribute to inequities (Kobus et al., 2013) with some reports indicating that these concerns are unfounded (Nelson, 2012; Kobus et al., 2013), however tensions surrounding this debate remain.

Teacher stress may also influence the implementation of BYOD in schools (Fogarty and Carr, 2014). Research suggests teachers lack of familiarity with devices (Liu et al., 2014) adds to pressures associated with classroom management and security. With emerging concerns about legal issues associated with ownership of these devices (Sweeney, 2012; Bathon, 2013) it may also be that parents may experience similar management and security challenges in relation to family practices with mobile devices in the home.

DOES BYOD IN PRIMARY SCHOOLS ENHANCE STUDENTS LEARNING?

Although limited, available research indicates that there is merit in the implementation of BYOD approaches and practices in primary schools (see Sweeney, 2012; Johnson et al., 2014). Research undertaken in secondary schools highlights the importance of relationships between parents, students, teachers, IT technicians, principals, and the wider community in contributing to a successful mobile-learning program (Ng and Nicholas, 2013). There are implications for these relationships being also understood in the primary school context.

In a literature review of mobile learning across education contexts K-12 Liu et al. (2014) identified studies where student access to mobile technologies was attributed to blurring boundaries between "formal and informal learning spaces" (p. 357) and extending learning from school into the home. Whether or not this is the case in primary schools is less certain which suggests that more needs to be known about the broader influences of BYOD on family life and school practices and vice versa.

CONCLUSION

The implementation of BYOD in primary schools is influenced by local school and family practices, and broader societal trends. This is similar to what Selwyn (2013) describes as the global and local contexts of implementation that has been evident in one laptop per child (OLPC) initiatives. The efficacy and long term sustainability of BYOD in primary schools cannot be determined without first understanding family and school practices in school communities where BYOD approaches are implemented. Future research may inform this process through a focus on understanding experiences from both parent and teacher perspectives. Until then, the implementation of BYOD in primary schools remains open to debate.

AUTHOR CONTRIBUTIONS

The author confirms being the sole contributor of this work and approved it for publication.

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Conflict of Interest Statement: The author declares that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

frontiers in Psychology

METHODS
published: 25 October 2016
doi: 10.3389/fpsyg.2016.01666

Can Touch Screen Tablets be Used to Assess Cognitive and Motor Skills in Early Years Primary School Children? A Cross-Cultural Study

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Assessment of cognitive and motor functions is fundamental for developmental and neuropsychological profiling. Assessments are usually conducted on an individual basis, with a trained examiner, using standardized paper and pencil tests, and can take up to an hour or more to complete, depending on the nature of the test. This makes traditional standardized assessments of child development largely unsuitable for use in low-income countries. Touch screen tablets afford the opportunity to assess cognitive functions in groups of participants, with untrained administrators, with precision recording of responses, thus automating the assessment process. In turn, this enables cognitive profiling to be conducted in contexts where access to qualified examiners and standardized assessments are rarely available. As such, touch screen assessments could provide a means of assessing child development in both low- and high-income countries, which would afford cross-cultural comparisons to be made with the same assessment tool. However, before touch screen tablet assessments can be used for cognitive profiling in low-to-high-income countries they need to be shown to provide reliable and valid measures of performance. We report the development of a new touch screen tablet assessment of basic cognitive and motor functions for use with early years primary school children in low- and high-income countries. Measures of spatial intelligence, visual attention, short-term memory, working memory, manual processing speed, and manual coordination are included as well as mathematical knowledge. To investigate if this new touch screen assessment tool can be used for cross-cultural comparisons we administered it to a sample of children ($N = 283$) spanning standards 1–3 in a low-income country, Malawi, and a smaller sample of children ($N = 70$) from first year of formal schooling from a high-income country, the UK. Split-half reliability, test-retest reliability, face validity, convergent construct validity, predictive criterion validity, and concurrent criterion validity were investigated. Results demonstrate "proof of concept" that touch screen tablet technology can provide reliable and valid psychometric measures of performance in the early years, highlighting its potential to be used in cross-cultural comparisons and research.

Keywords: assessment, cognitive development, fine motor skills, touch-screens, Malawi, developing countries, cross-cultural comparison

OPEN ACCESS

Edited by:
Gabrielle Strouse,
University of South Dakota, USA

Reviewed by:
Rachel M. Flynn,
New York University, USA
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Specialty section:
This article was submitted to Developmental Psychology, a section of the journal Frontiers in Psychology

Received: *30 June 2016*
Accepted: *11 October 2016*
Published: *25 October 2016*

Citation:
Pitchford NJ and Outhwaite LA (2016) Can Touch Screen Tablets be Used to Assess Cognitive and Motor Skills in Early Years Primary School Children? A Cross-Cultural Study. Front. Psychol. 7:1666. doi: 10.3389/fpsyg.2016.01666

INTRODUCTION

There are very few cross-cultural tools for assessing early child development. Yet assessment of core cognitive and motor skills in the early years is important for evaluating health and educational interventions, which can help guide policy and best practice to optimize development in early childhood (Sabanathan et al., 2015; Zuilkowski et al., 2016), and enhance the economic potential for disadvantaged children around the world (Heckman, 2006). Here, we consider if touch screen tablet technology can provide an innovative solution to assessing core cognitive and motor skills in the early years that can be used in both low- and high-income countries to identify children at risk of underachievement. We present a new touch screen tablet-based assessment tool that includes measures of core cognitive and motor skills thought to be associated with scholastic progression. We report on initial trials of this new touch screen assessment tool in two representative locations, one high-income country in Europe, the UK, and one low-income country in Sub-Sahara Africa, Malawi, to examine its potential as a cross-cultural tool. These two countries not only differ vastly in gross domestic product, with Malawi being one of the poorest countries and the UK being one of the richest countries in the world (World Bank, 2015[1]), they also differ in culture and education systems. Evaluating the reliability and validity of this new touch screen assessment tool with children attending the early years of primary school from these two countries thus provides a critical test of "proof of concept" that touch screen tablets can be used for cross-cultural psychometric measurements of core cognitive and motor skills.

Sabanathan et al. (2015) highlight five key global developmental domains important in the assessment of a child's developmental progress: (i) cognitive skills, including memory and information processing, (ii) language skills, including receptive and expressive language, (iii) motor skills, including fine motor and gross motor skills, (iv) social and emotional skills; including the ability to understand their own and others emotional states and (v) adaptive behavior skills, including conceptual, social, and practical skills for everyday functioning.

It is thus essential that reliable and valid cross-cultural methods of assessing these key global developmental functions are available across low-to-high-income countries to enable identification of those children most at risk of educational underachievement and in need of intervention support.

While there are a range of cultural specific child development assessment tools (Thompson and Vacha-Haase, 2000), some of which are recommended by funding bodies for global health and education research (Fernald et al., 2009), there are few cross-culturally valid assessments of basic cognitive and motor functioning. There is also limited research evaluating their cross-cultural usability and psychometric properties (Sabanathan et al., 2015). Yet, cross-cultural assessment tools of basic cognitive and motor functions are important if international comparisons of early child development and the theoretical underpinnings are to be sought. However, assessing core developmental skills cross-culturally poses a number of challenges, as outlined in the following section.

[1]The World Bank, "GDP per capita (current US$)" (The World Bank Group, 2015) http://data.worldbank.org/indicator/NY.GDP.PCAP.CD.

Practical Challenges

Most standardized assessments of cognitive, motor, and language skills require strict administration procedures, which necessitates highly trained assessors (Sabanathan et al., 2015), and in some cases controlled laboratory settings (Zuilkowski et al., 2016), which are frequently unavailable in developing countries (Scherzer et al., 2012). Moreover, these assessments are costly and timely to administer. This makes these types of standardized assessments, which are commonly used in high-income countries to identify children at risk of learning difficulties, prohibitive for use in developing countries. To profile strengths and weaknesses of individual children in low-to-middle-income countries, an assessment tool is needed that is low cost, easy to use, and easy to interpret by practitioners with a general training in early child development.

Construct Bias

Construct bias encompasses cultural differences in how the target skills are operationalized. For example, the construct of intelligence in rural Kenya includes four dimensions: social qualities, practical thinking, comprehension, and academic achievement. Western measures of intelligence correlate with only one aspect of the Kenyan constructs, academic achievement (Grigorenko et al., 2001). An assessment tool that focuses on core cognitive and motor skills would thus alleviate cultural differences in constructs of intelligence, and focus instead on key functions required for scholastic progression.

Method and Item Bias

Methods bias includes differences in assessment administration, such as, the language and medium of delivery and stimuli used, that may favor one group over another (Matafwali and Serpell, 2014). This, in turn, may also impact on item bias, which refers to differences in observed performance despite equal abilities on a particular skill based on participants' cultural or linguistic background. Cross-cultural studies have shown biases in task performance based on different language structures (Jukes and Grigorenko, 2010), and different levels of stimulus familiarity (Callaghan et al., 2012; Zuilkowski et al., 2016). For example, in an attempt to address item bias when adapting a neuropsychological test used in Western cultures to be accessible for the Indonesian population, Prado et al. (2010) changed a picture stimulus of a "bunny" to a "chicken." However, despite these modifications, young children were still unable to complete the assessment successfully (Abubakar et al., 2008). This may have resulted from other age or language related biases that may have restricted children's participation, in that children might not have understood the task in hand. Assessment tools for cross-cultural use in early child development will benefit from minimal and simple task instructions, that require non-verbal responses to be made, and use stimuli that are acquired early in life and transcend cultures, such as basic shapes and colors (Bornstein et al., 1976).

Lack of Normative Data

Standardized assessments that are commonly used in high-income countries often lack normative data for low-to-middle-income countries, rendering them unsuitable for use in the developing world. Standardizing assessments is non-trivial and traditional approaches that make use of paper and pencil administration require high investment in time and resources to produce reliable norms that span the developmental timeframe when key cognitive, motor, language and scholastic skills are learnt (preschool to late adolescence). In developing an assessment tool to be used in low-to-middle-income countries innovative methods of collecting normative data that are reliable and rapid are needed and touch screen assessment tools need to be sensitive to maturational processes.

Recent Progress

In spite of these challenges, recent progress has been made in developing valid cognitive and motor assessments for use in specific developing countries, particularly in the fields of health and education (Jukes and Grigorenko, 2010). For example, cognitive assessments, including motor skills, executive function, and language abilities, have been developed specifically for Zambia (Serpell, 1974; Ezeilo, 1978; Fink et al., 2013), rural Kenya (Kitsao-Wekulo et al., 2012), Bangladesh (Khan et al., 2013), and Malawi (Gladstone et al., 2009, 2010) populations. Assessment designed to determine young children's developmental milestones have also been developed in South Africa (Boyede et al., 2016), Malawi (Gladstone et al., 2009, 2010), Kenya (Prado et al., 2010), Nigeria (Eseigbe, 2013), and Cambodia (Ngoun et al., 2012).

These assessments are designed to be administered by trained assessors and usually involve observational checklists (e.g., Gladstone et al., 2009, 2010; Boyede et al., 2016), parental reports (e.g., Ngoun et al., 2012), or require a battery of specific resources (e.g., Jukes and Grigorenko, 2010). These methods, while insightful, can be expensive and timely to administer, and usually focus on measuring developmental milestones that typify early child development prior to school entry (Gladstone et al., 2009, 2010). Thus, they may not be sustainable for use outside of the research context. They are also country-specific so cannot be used to make cross-cultural comparisons. A generic assessment tool is thus needed, that is both reliable and valid across different cultures, which is cross-validated with scholastic performance, to enable cross-cultural studies of child development to be conducted, and a universal framework of factors that influence progress through school to be developed.

Several international bodies, including the Malawi Institute of Education (2014), have called for modern forms of data collection that utilize mobile devices, which have the ability to collect valid and reliable outcome data, and reduce time and monetary costs. Tablet-based versions of international numeracy and literacy assessments, such as, the Early Grade Mathematics Assessment, EGMA (Brombacher, 2010) and the Early Grade Reading Assessment, EGRA (Gove and Wetterberg, 2011) have been developed by RTI international. However, these require a trained evaluator to administer questions and record individual children's responses through the tablet. They do not capitalize on the touch screen tablet technology that can be used to record responses directly from individual children in response to particular tasks. As such, the tablet versions of EGMA and EGRA still require one-to-one administration, which is costly both in time and human resources.

Current Study

We have developed a new touch screen tablet-based assessment tool for cross-cultural comparisons of core cognitive and motor skills in primary school children that addresses the challenges and limitations discussed. The new assessment tool was designed by the first author and programmed by onebillion, a UK-based charity. We report on the initial stage of its development, through trials with children attending the first 3 years of primary school in Malawi and the first year of primary school in the UK. To demonstrate "proof of concept" we need to show that the touch screen assessment tool is reliable and valid across cultures.

Constructs Measured

This new touch screen assessment tool includes measures of manual processing speed, manual coordination, short-term memory, visual attention, working memory, and spatial intelligence. These cognitive and motor measures were chosen because of their close association with the development of fundamental scholastic skills, such as mathematics and literacy (e.g., Nunes et al., 2007; Berg, 2008; Mulder et al., 2010; Westerndorp et al., 2011; Bourke et al., 2014; Simms et al., 2014; Pitchford et al., 2016). Accordingly, a measure of scholastic skill - mathematics - that is taught from the start of formal schooling in both Malawi and the UK was also included to cross-validate the new assessment tool.

Item Stimuli

The stimuli used to assess core cognitive and motor skills centered on basic shapes and colors, as these are easily discriminable, acquired at an early age, and commonly occur in urban and semi-urban environments (e.g., Bornstein et al., 1976). Basic shapes, such as squares, rectangles and circles, are represented even in rural environments in developing countries, such as village houses and churches, and basic colors are frequent in the clothing worn by both rural and urban people.

Assessment Delivery

This new assessment tool utilizes touch screen technology as its method of delivery and recording responses from individual child. All tasks required a non-verbal, manual, response, to be made. Recent research with high-income countries has demonstrated the usability, affordance and potential for using tablet technology for collecting cognitive development data with young children in a research setting (Semmelmann et al., 2016). However, to our knowledge, our touch screen assessment tool is the only direct measure of child performance across a range of neuropsychological tasks shown to be associated with developmental disorders and scholastic progression that has been trialed across both low- and high-income country contexts.

The use of touch screen tablet technology in the assessment of cognitive and fine motor abilities offers several unique affordances. Tablet technology is lightweight and eliminates the need for other devices that may rely on developed motor skills (Donker and Reitsma, 2007; Kucirkova, 2014). Even young children (aged 2–3 years) have the required motor skills to use touch screen technology (Nacher et al., 2015). Furthermore, apps are available for assessing and training fine motor skills that are grounded in occupational therapy techniques (e.g., Dexteria, Kizony et al., 2016; Short et al., in press) thus illustrating that touch screen technologies are suitable for use in assessing core skills in primary school aged children. Furthermore, tablet technology allows standardized procedures for all children and so eliminates researcher or teacher bias and reduces measurement error. Consequently, there has been an increase in the use of touch screen technology in cognitive assessments in the West. For example, Pearson Education Ltd[2] have developed Q-interactive, a tablet-based tool for administering a number of cognitive assessments traditionally administered in a paper and pen format. Despite the advances in tablet technology based assessments in high-income countries, there is a significant gap in resources for developing countries that needs to be addressed.

METHODS

We evaluated this new touch screen tablet-based assessment tool for reliability and validity in early years populations from both Malawi and the UK. Reliability and validity measures were based on the basic psychometric properties used to evaluate child development assessment tools outlined by Sabanathan et al. (2015).

Participants

The Malawi sample consisted of 283 children from Standards 1–3 (the first 3 years of education in Malawi) attending a state primary school located in an urban area of Lilongwe, the capital of Malawi. The sample consisted of 144 males and 139 females. Age ranged between 73 and 161 months[3] ($M = 97.15$ months, $SD = 15.16$ months; median age = 94.00 months). Any learning difficulties were unknown. The Ministry of Education in Malawi gave consent for the study to take place and selected the participating primary school. Consent was also obtained from the parent association at the primary school and the Community Chief of the region where the primary school is located.

The UK sample consisted of 70 pupils in Foundation 2 (the first year of compulsory education in the UK) attending a primary school situated in Nottingham, a metropolitan city in the United Kingdom. The sample consisted of 39 males and 31 females. Age ranged between 50 and 69 months ($M = 60.81$, $SD = 4.98$). Two children in the sample were identified to have special educational needs in the form of mild autistic spectrum disorder. Eight children were absent at the time of data collection for standardized measures used for validation purposes and so were excluded from the associated data analyses. This study was granted ethical approval from the ethics committee at the School of Psychology, University of Nottingham, and written parental consent was obtained for all participating children prior to study commencement.

For each sample, outliers (defined as 2 standard deviations or more above and below the group mean) for each of the cognitive and motor tasks included in the new assessment tool were excluded from the analysis. **Table 1** describes the final Malawi and UK samples for each task.

Tablet-Based Assessment Measures

All participating children were assessed on six measures of cognitive development: manual processing speed, manual coordination, short-term memory, visual attention, working memory, and spatial intelligence. A measure of mathematics was also given, that included assessment of both curriculum and conceptual knowledge. Each task is described in the following section and is illustrated in **Figure 1**.

Manual Processing Speed

A single-finger-tapping task was used to assess manual processing speed (see Witt et al., 2008). Using the index finger of their dominant hand children were required to tap a green box displayed on the screen continually, as fast as they could, which caused a blue balloon to increase in size. The task was complete when the child had tapped the green box 30 times causing the balloon to pop. An overall measure of manual processing speed was calculated from the mean completion time across the two trials.

Manual Coordination

Manual coordination was assessed using an alternating finger tapping task (see Witt et al., 2008). Similar to the manual processing speed task, stimuli consisted of two green boxes and one blue and one purple balloon. Children were required to tap each of the two green boxes alternatively, with the index finger of their left and right hand, to pop the two balloons. Balloons would only increase in size if the child tapped each green box alternately with their left then right index finger. Each box required tapping 30 times in sequence for the balloon to pop. An overall measure of manual coordination was calculated from the mean completion time across the two trials.

Short-Term Memory

A forward spatial span task was used to assess short-term memory, similar to that used by Brunetti et al. (2014). Children were presented with a three-by-three grid of yellow circles. The virtual instructor demonstrated the pattern to be recorded by the child by touching the yellow circles. When the demonstrator touched a yellow circle it turned red, momentarily, until the demonstrator touch the next circle in the sequence. Children were then required to repeat the order they had been presented. The number of circles included in the pattern increased in line

[2] Pearson Education Limited (2013). *Introducing Q-interactive.* Retrieved June 28, 2016 from http://www.helloq.co.uk/content/dam/ped/ani/uk/helloq/downloads/introducing-q-interactive.pdf.

[3] In Malawi children can repeat years if they fail to progress so our sample includes some older children who were repeating years 1–3 of primary school.

TABLE 1 | Structure of the Malawi and UK samples for each task.

Task	Malawi					UK				
	n	Gender	Age (months)			*n*	Gender	Age (months)		
		M:F	Range	M (SD)	Median		M:F	Range	M (SD)	Median
Manual processing speed	261	134:127	73–161	97.54 (15.30)	96.00	62	36:26	50–69	60.94 (4.82)	61.00
Manual coordination	218	107:111	74–161	100.82 (14.75)	99.00	64	36:28	50–69	60.94 (4.75)	61.00
Short-term memory	215	105:110	74–161	99.30 (14.27)	98.00	69	38:31	50–69	60.72 (4.96)	61.00
Visual attention	233	117:116	73–161	98.70 (15.50)	98.00	62	36:26	50–69	60.51 (5.01)	61.00
Working memory	221	109:112	74–161	99.29 (14.50)	98.00	67	36:31	50–69	60.96 (4.88)	61.00
Spatial intelligence	223	105:118	74–161	99.35 (14.75)	98.00	66	36:30	50–69	60.74 (5.07)	61.00
Mathematics	266	132:134	73–161	96.42 (15.06)	94.00	59	36:23	50–69	60.37 (5.09)	60.00

with progression through the test, starting at 1 and increasing to 9. The task discontinued after three successive incorrect trials. The number of trials completed correctly gave the overall short-term memory score.

Visual Attention

Visual attention was assessed through a speeded search task, similar to that used by Pitchford et al. (2011). Before each of three experimental trials, children were presented with a baseline practice trial in which they were shown a single colored dot, followed by an array of either 8, 12, or 16 same colored dots, which they were instructed to touch as fast as they could. In the experimental trials, children were required to distinguish and touch all the colored dots given in the practice trial from a display of different colored distracter dots. For each trial, time taken to complete the baseline trial was subtracted from the time taken to complete the experimental trial, thus generating a measure of visual attention that was not confounded by manual processing speed. An overall measure of visual attention was derived from the mean response times taken to complete the three experimental trials.

Working Memory

A backward spatial span task was used to assess working memory, similar to that used by Brunetti et al. (2014). The task followed the same layout and characteristics as the short-term memory, forward spatial span, task, except that children were required to repeat the presented pattern backwards. The number of circles included in the pattern increased in line with progression from 2 to 9. The task discontinued after three successive incorrect trials. An overall working memory score was calculated on the number of correct trials completed.

Spatial Intelligence

Spatial intelligence was assessed using a two-dimensional pattern-processing task, similar to the three-dimensional Block Design task used in standardized assessments (e.g., Wechsler, 2003). The task required children to reconstruct a two-dimensional pattern using simultaneously displayed pattern squares. The number of pattern squares available depended on the size of the presented pattern that children were required to recreate. The task discontinued after three successive incorrect trials. An overall spatial intelligence score was obtained from the number of correct patterns recreated.

Mathematics

A test consisting of 98 items, measuring different aspects of curriculum and conceptual knowledge was used to assess mathematics. The curriculum questions were based on the content of the onebillion mathematics apps (Pitchford, 2015) that are grounded in the UK national curriculum, and cover topics such as counting, addition, subtraction, and shape and space recognition. The mathematics curriculum in Malawi is based on the UK curriculum and places a strong focus on the acquisition of numeracy skills (Chirwa and Naidoo, 2014). The conceptual questions were based on the Early Grade Mathematics Assessment (EGMA; Brombacher, 2010) and the Numerical Operations subtest of the WIAT-II (Wechsler, 2005; see Pitchford, 2015). Concepts assessed included symbolic understanding, numbers in relation to each other, number line understanding, counting, number sense (quantity estimation), simple and complex addition and subtraction, multiplication, and division. Task difficulty increased in line with task progression and discontinued after three successive incorrect answers. An overall mathematics score was determined from the total number of questions answered correctly.

Standardized Measures (UK Only)

To assess the criterion validity of the new touch screen tablet assessment tool, children in the UK sample were also given two standardized measures of cognitive development, namely the Block Design and Symbol Search subtests from the WPPSI-III (Wechsler, 2003). These Western based standardized measures were chosen as they are similar to the cognitive skills measured in the new tablet assessment. In particular, we predicted that performance on the Block Design subtest from the WPPSI-III should correlate with the task of spatial intelligence on the new touch screen tablet assessment as both are designed to measure spatial reasoning skills. Likewise, we expected performance on the Symbol Search subtest from the WPPSI-III to correlate with the tasks of manual processing speed, short-term memory, and working memory. This is because the Symbol Search subtest from the WPSSI-III is a measure of cognitive processing speed which

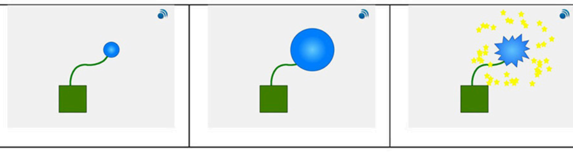
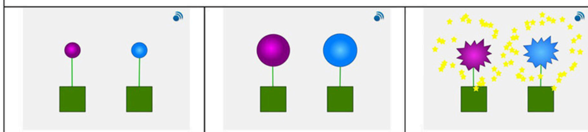
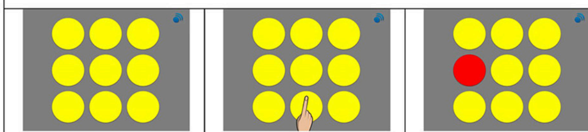
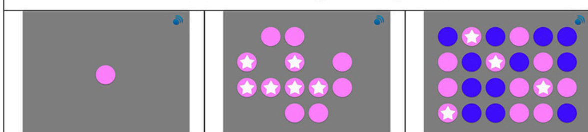
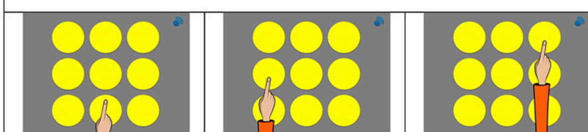
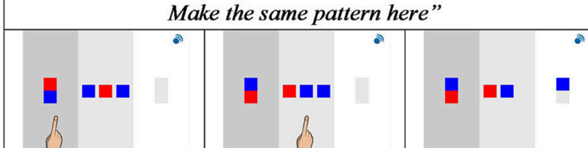
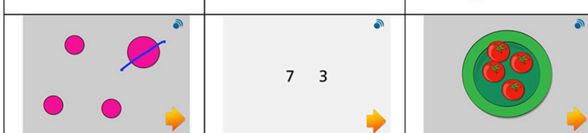
Task Order	Function Measured	Task stimuli & task instructions
1	Manual Processing Speed	*"Tap the green square as fast as you can"* 
2	Manual Coordination	*"There are two green squares. Touch one square then the other as fast as you can"* 
3	Short-Term Memory	*"Copy me"* 
4	Visual Attention	*"Touch the pink dot. Touch all the pink dots as fast as you can. Remember touch just the pink dots"* 
5	Working Memory	*"Watch me. You do it backwards"* 
6	Spatial Intelligence	*"Look at this pattern. Use these blocks. Make the same pattern here"* 
7	Mathematics	*"Cross out the odd one out"*; *"Touch the biggest number"*; *"Put four tomatoes on the plate"* 

FIGURE 1 | Schematic illustration of tasks included in the new touch screen tablet-based assessment of cognitive and mathematical skills for primary school children.

is known to be dynamically related to working memory (Kail and Salthouse, 1994; Fry and Hale, 1996) and in young children working memory and short-term memory are highly correlated (Hornung et al., 2011; Aben et al., 2012).

Block Design

The Block Design subtest of the WPPSI-III requires children to recreate block patterns presented as a constructed model or picture using one or two colored blocks within a specified time. The task is designed to test ability to analyse and synthesize abstract visual stimuli and is an assessment of non-verbal, spatial intelligence, and visual-motor coordination (Sattler, 2001). This measure has good internal consistency for children aged 4–5 years, ranging from 0.76 to 0.85, as reported in the test manual (Wechsler, 2003, p. 52). Raw scores were used.

Symbol Search

The Symbol Search subtest of the WPPSI-III requires children to identify whether or not an abstract target symbol is present amongst an array of other similar symbols. The task is designed to assess processing speed and incorporates visual short-term memory and visual-motor coordination (Sattler, 2001). Similar to the Block Design, this measure has good internal consistency for children aged 4–5 years, ranging from 0.76 to 0.85, as reported in the test manual (Wechsler, 2003, p. 52). Raw scores were used.

Procedure

All children completed the touch screen tablet assessments independently, which were delivered through an individual iPad mini connected to a set of headphones, whilst they were sat on the floor of their classroom. Tasks were presented in the order outlined above and as listed in **Figure 1**. A virtual instructor delivered task instructions in the child's local language (Chichewa in Malawi; English in the UK). The child could repeat task instructions on demand by touching a small button in the corner of the screen. The virtual instructor demonstrated this at the start of the assessment tool, during a familiarization task.

The familiarization task included at the start of the new tablet assessment tool taught children how to perform the operations required for the using the tablet to complete the individual tasks. For example, demonstrations were given by the virtual instructor in how to select and move objects around the touch screen then children were given the opportunity to practice these actions. The familiarization task also had immediate positive feedback on correct responses in the form of a tick and high-pitched sound. Feedback was only given during the familiarization task to encourage children who were using the tablet for the first time.

In Malawi, the new tablet assessment tool was administered in groups of up to 50 children. The total group of 283 children completed the new assessment tool on two occasions, with an interval of 8-weeks between administrations. In the UK, the new tablet assessment tool was administered in groups of up to 15 children. The total group of 70 children completed the new assessment tool just once. **Figure 2** illustrates the assessment tool being administered to groups of children in Malawi and the UK.

For both samples, individual tasks were demonstrated to children by the researcher before the start of each task. In Malawi, teaching staff and a volunteer from the Voluntary Service Overseas supervised the group administration, so as to provide language support for the English-speaking researcher (first author) whilst she demonstrated the tasks. Data for individual children was recorded by the tablets and later retrieved through an Internet server hosted by onebillion, the UK charity supporting this project. For the UK sample, after completing the new tablet assessment tool with groups of children, the two standardized measures were given in a separate session to individual children, by the researcher (second author), in a quiet area, free from distraction, in their familiar school environment. Block Design was given first, followed by Symbol Search.

RESULTS

To evaluate different aspects of reliability and validity of the new touch screen tablet-based assessment tool a series of correlations was conducted for each sample. A two-tailed level of probability was adopted in all analyses, despite some directional hypotheses being made.

Tables 2, 3 report Cronbach's Alpha and Pearson's Product Moment correlation coefficients for each of the following investigations.

Split-Half Reliability

The three timed tasks (manual processing speed, manual coordination, and visual attention) included more than one trial so internal consistency was investigated for each of these tasks, for each sample, by correlating performance across trials using Cronbach's Alpha correlation coefficients. For both samples, significant, moderate to strong, positive correlations were found across trials for each of the three timed tasks (**Table 2**).

Test-Retest Reliability

The Malawi sample was given the new touch screen assessment tool on two occasions, separated by a 8-week interval, enabling consistency over time to be investigated each task, by correlating performance across the first and second administration[4]. Significant, moderate to strong, positive correlations were found across repeated administration of all tasks, except for working memory and spatial intelligence where weak correlations were found (**Table 2**).

Face Validity

The new touch screen assessment tool should be sensitive to developmental progression, in that performance should increase with age. Thus, face validity was established by correlating age (months) with task performance for all of the measures included in the new assessment tool. Results revealed negative, moderate correlations with age for each of the three timed tasks (manual processing speed, manual coordination, and visual

[4]Test-retest reliability for Mathematics was conducted with a third of the Malawi sample only, all of who received standard teaching practice across the 8-week interval between first and second administration. The rest of the Malawi sample received a specific mathematics intervention during the intervening 8-week period between assessments, which might have influenced test-retest reliability results, so these children were not included in the test-retest reliability measure for Mathematics.

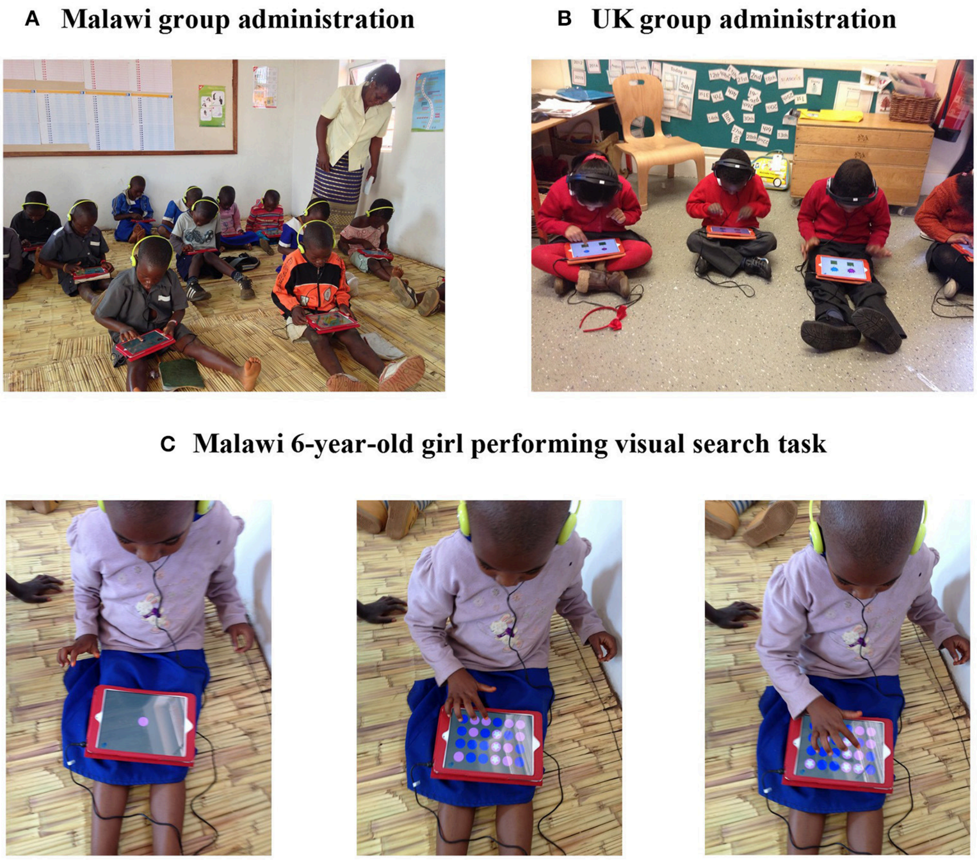


FIGURE 2 | Group administration of the new touch screen tablet-based assessment with primary school children in Malawi (A) and the UK (B). Six-year-old girl in Malawi performing the visual attention task **(C)**.

TABLE 2 | Reliability and validity analyses for Malawi and UK samples.

Task	Correlations (*r*)								
	Malawi				UK				
	Split-half reliability	Test-retest reliability	Age	Predictive criterion validity[a]	Split-half reliability	Age	Predictive criterion validity[a]	Criterion validity: Block design	Criterion validity: Symbol search
Manual processing speed	0.50**	0.35**	−0.29**	−0.23**	0.53**	−0.35**	−0.18	0.03	−0.25*
Manual coordination	0.93**	0.16**	−0.16*	−0.04	0.88**	−0.10	0.03	0.05	0.07
Short-term memory	–	0.34**	0.13	0.21**	–	0.10	0.23*	0.17	0.37**
Visual attention	0.40**	0.42**	−0.34**	−0.34**	0.44**	−0.25*	−0.16	−0.11	−0.16
Working memory	–	0.05	0.07	−0.06	–	0.04	0.29*	0.24*	0.36**
Spatial intelligence	–	0.12	0.13	0.20**	–	0.08	0.31**	0.33*	0.15
Mathematics	–	0.73** (*n* = 77)	0.39**	–	–	0.30*	–	–	–

***p < 0.001, * p < 0.05.*
[a] *Predictive criterion validity: correlation coefficients for each of core cognitive and motor tasks and Mathematics. A reduced sample size of 77 pupils was used for the Malawi test-retest reliability of the Mathematics task.*

attention), demonstrating faster performance by older children. For both samples, these age-related correlations were significant, except for manual coordination in the UK sample where a weak, non-significant, correlation was found. Likewise, positive correlations were found with age for each of the three core accuracy tasks (short-term memory, working memory, and

TABLE 3 | Convergent construct validity: correlation matrix across all six tasks for Malawi and UK samples.

Task	Correlations (r)									
	Malawi					UK				
	Manual processing speed	Manual coordination	Short-term memory	Visual attention	Working memory	Manual processing speed	Manual coordination	Short-term memory	Visual attention	Working memory
Manual coordination	0.17**	–				0.16	–			
Short-term memory	−0.9	−0.08	–			−0.20	−0.16	–		
Visual attention	0.26**	0.13*	−0.18**	–		0.16	0.14	−0.18	–	
Working memory	−0.07	0.13*	0.003	0.03	–	−0.11	−0.17	0.31**	−0.02	–
Spatial intelligence	−0.04	−0.01	0.14*	−0.24**	0.05	0.01	−0.15	0.48**	−0.18	0.31**

***p < 0.001, *p < 0.05.*

spatial intelligence), demonstrating better performance by older children. However, in both samples, only weak correlations were found with the three tablet-based tasks measuring accuracy of response, which were not significant, suggesting these measures are not particularly sensitive to developmental progression. In contrast, age correlated significantly with mathematics, as moderate and positive correlations were found of similar strength across cultures, illustrating that with increasing age knowledge of mathematical curriculum and concepts increases, as expected over the first years of primary school (**Table 2**).

Convergent Construct Validity

The three tasks measuring speed of response (i.e., manual processing speed, manual coordination, and visual attention) should correlate positively with one another across both samples. Likewise, the three tasks measuring performance accuracy (i.e., short-term memory, working memory, and spatial intelligence) should correlate positively with one another across both samples. To investigate convergent construct validity for the three tasks involving speed of response and the three tasks measuring accuracy of response a correlation matrix was produced, with partial correlations controlling for age.

As predicted, in both samples, positive correlations, of similar strength, were found amongst the three tasks measuring speed of response. These were significant for the larger Malawi sample but were not significant in the smaller UK sample (see **Table 3**). Likewise, in both samples, positive correlations were found amongst the three tasks measuring performance accuracy. Whilst moderate, significant, correlations were found in the UK sample amongst all three accuracy tasks, in the Malawi sample only the correlation between short-term memory and spatial intelligence was significant. Both correlations involving working memory were weak and not significant in the Malawi sample, suggesting the working memory measure within this sample has limited construct validity (see **Table 3**).

Predictive Criterion Validity

To further explore how the six tasks included in the new assessment tool predicted mathematical knowledge, partial correlations were performed for each tablet-based task and mathematics, controlling for age. In addition, to establish the contribution that each of the core cognitive and motor tasks made to mathematics performance, stepwise linear regression was used by entering the three accuracy tasks at step 1 followed by the three speeded tasks at step 2.

Results showed the core cognitive and motor tasks included in the new touch screen assessment tool correlated with mathematics performance in the expected direction. As shown in **Table 2**, negative correlations were found between each of the three timed tasks (manual processing speed, manual coordination, and visual attention) and mathematics for both samples, and these were of moderate strength and significant in the Malawi sample, except for manual coordination. Although in the predicted direction, weak correlations were found in the UK sample between each of the three timed tasks and mathematics, none of which were significant. For the three accuracy measures (short-term memory, working memory, and spatial intelligence) and mathematics, significant, positive correlations, of moderate strength, were found in both samples, except for working memory in the Malawi sample where a very weak negative correlation was found.

Stepwise linear regression analyses revealed a similar amount of variance in mathematics performance was accounted for by the core cognitive and motor tasks included in the new touch screen assessment tool. As shown in **Table 4**, for both samples, 15% of the total variance was accounted for by the tablet-based cognitive and motor tasks. Whilst the model fits were significant for the larger Malawi sample, the model fits were not significant for the smaller UK sample, indicating a lack of power in the UK sample with six predictor variables. For the Malawi sample, the tasks of spatial intelligence and manual processing speed contributed significantly to the model fit, accounting for 8 and 7% of the total variance respectively. In the UK sample, the only significant predictor of mathematical performance was manual processing speed, which accounted for 10% of the total variance.

Concurrent Criterion Validity

The UK sample was also given two standardized subtests of the WPSSI-III. This enabled concurrent criterion validity to be investigated by conducting partial correlations between the six core cognitive and motor tasks included in the new touch screen assessment tool and performance on the two standardized sub-tests of the WPSSI-III, using raw scores and controlling for age.

TABLE 4 | Predictive criterion validity: linear regression models to examine variance in mathematics accounted for by accuracy and timed tasks in Malawi and UK samples.

Model	Variable(s)	Model		Significance	Change		Unstandardized coefficients	Standardized coefficients	Significance
		R	R^2	*F (df), p*	ΔR^2	Sig. ΔF	*B*, Std. Error	Beta	*t, p*
MALAWI									
1	**Accuracy tasks**	0.28	0.08	3.37 (3, 123),	0.08	$\mathbf{p = 0.021}$			
	Short-term memory			$\mathbf{p = 0.021}$			1.13, 2.78	0.16	1.82, $p = 0.071$
	Working memory						−1.49, 1.34	−0.10	−1.11, $p = 0.269$
	Spatial intelligence						2.03, 0.90	0.20	**2.25,** $\mathbf{p = 0.027}$
2	**Accuracy tasks**	0.39	0.15	3.51 (6, 120),	0.07	$\mathbf{p = 0.019}$			
	Short-term memory			$\mathbf{p = 0.003}$			0.95, 0.61	0.13	1.55, $p = 0.123$
	Working memory						−1.54, 1.31	−0.10	−1.18, $p = 0.241$
	Spatial intelligence						1.74, 0.89	0.17	1.95, $p = 0.053$
	Timed tasks								
	Manual processing speed						−0.001, <0.0001	−0.20	**−2.29,** $\mathbf{p = 0.024}$
	Manual coordination						0.00002, <0.0001	0.02	−0.24, $p = 0.813$
	Visual attention						−0.007, 0.005	−0.14	−1.55, 0.123
UK									
1	**Accuracy tasks**	0.23	0.05	0.74 (3, 40),	0.05	$p = 0.534$			
	Short-term memory			$p = 0.534$			−0.37, 1.12	−0.06	−0.33, $p = 0.743$
	Working memory						0.66, 2.41	0.05	0.28, $p = 0.785$
	Spatial intelligence						1.29, 0.98	0.23	1.32, $p = 0.194$
2	**Accuracy tasks**	0.39	0.15	1.13 (6, 37),	0.10	$p = 0.232$			
	Short-term memory			$p = 0.363$			−0.74, 1.12	−0.11	−0.66, $p = 0.514$
	Working memory						−0.14, 2.45	−0.01	−0.06, $p = 0.956$
	Spatial intelligence						1.85, 1.00	0.33	1.84, $p = 0.073$
	Timed task								
	Manual processing speed						−0.003, 0.001	−0.33	**−2.06,** $\mathbf{p = 0.047}$
	Manual coordination						0.00007, <0.0001	−0.05	−0.29, $p = 0.774$
	Visual attention						0.01, 0.01	0.11	0.64, $p = 0.524$

Significant results highlighted in bold.

As predicted, a significant, positive correlation, of moderate strength, was found between Block Design and the tablet measure of spatial intelligence, as both tasks were designed to measure spatial reasoning skills (see **Table 2**). In addition, the tablet measure of working memory also correlated significantly with Block Design, presumably because it was a visuo-spatial working memory task. Likewise, significant correlations, of moderate strength, were found in the predicted direction between Symbol Search and the tablet measures of manual processing speed, short-term memory, and working memory. This was expected because the Symbol Search subtest of the WPSSI-III is designed to measure cognitive processing speed, which is dynamically related to working memory and short-term memory in early childhood.

DISCUSSION

We have demonstrated "proof of concept" that touch screen tablet technology can be used for cross-cultural assessments of core cognitive and motor functions associated with scholastic progression, in the early primary years. The new assessment tool that we describe was trialed with samples of children attending the first years of primary school in two countries, one high-income (UK) and one low-income (Malawi), which differ radically in culture and educational context. Despite these differences, results showed remarkably similar patterns of reliability and validity across samples, for children's performance on the new touch screen assessment tool, demonstrating its potential to be used in cross-cultural comparisons and research.

Results showed the new touch screen assessment tool had good internal consistency for timed measures including multiple trials in both the Malawi and UK samples. In the Malawi sample, moderate test-retest reliability was shown for the majority of tasks, and for both samples, reasonable face validity was demonstrated, in that task performance correlated with age. Specifically, age correlated negatively with performance on the three tasks measuring speed of response and positively (albeit weakly) with the three tasks where accuracy of response was measured. These results are consistent with previous research demonstrating reduced reaction times on a computer-assisted reaction time task and increased performance on Ravens progressive matrices in line with chronological and educational age (Van de Vijver and Brouwers, 2009). In addition, significant, positive correlations with age and mathematics were found across cultures, demonstrating that touch screen technology can provide a valid means of measuring scholastics skills that are taught from the start of primary school.

Reasonable convergent construct validity was also shown across cultures for the six tasks included in the new touch screen assessment tool. As predicted, in both samples, the three tasks measuring speed of response correlated with one another, as did the three tasks measuring accuracy of response. This corroborates a robust body of evidence demonstrating interrelations between different cognitive and motor skills during development (see Diamond, 2000, 2007, for reviews). However, within the Malawi sample, both correlations involving working memory were weak and not significant. The lack of correlation with working memory within the Malawi sample might arise from generally low levels of performance on this task. Despite a broader age range (first 3 years of primary school) in the Malawi sample than the UK sample, performance on the working memory task was significantly lower in the Malawi sample than the younger sample of UK children [Malawi, $M = 0.48$, $SD = 0.71$; UK, $M = 0.79$, $SD = 0.94$, $t_{(286)} = 2.87$, $p = 0.004$].

Working memory typically starts to develop around 4 years in Western cultures (Gathercole et al., 2004). This coincides with when children typically start school in the UK and formal schooling enhances working memory (Kosmidis et al., 2011). However, in Malawi, formal schooling and quality education is limited, due to high student-teacher ratios, a shortage of qualified teachers, short school days, and limited teaching resources (Hubber et al., 2016). Consequently, Malawi education relies on rehearsal, rather than deeper forms of learning involving simultaneous storage and processing, which typify UK classroom activities. Thus, the education context in Malawi may account for the observed poor working memory performance and lack of correlations between working memory and the other cognitive tasks measuring performance accuracy found here.

Similarly, predictive criterion validity was established across cultures. When the three tasks measuring accuracy of response and the three tasks measuring speed of response were entered into a regression model predicting mathematical ability, 15% of the total variance was accounted for within each sample. Manual processing speed contributed uniquely to the model fits in both samples, indicating this measure is a cross-cultural predictor of early mathematical ability. Recent studies have identified fine motor skills to be a significant predictor of mathematical ability in Western populations (Becker et al., 2014; Cameron et al., 2016; Pitchford et al., 2016). However, the tasks used to measure fine motor skills in these studies often include an aspect of spatial processing (Barnhardt et al., 2005; Simms et al., 2016), making it difficult to determine if it is the spatial or fine motor skills that are predictive of early mathematical ability. Whilst the two tasks of fine motor skill included here have limited spatial processing, only the task of manual processing speed predicted mathematical ability. This indicates that it is the measurement of processing speed, rather than fine manual control *per se*, that is contributing significantly to predicting early mathematical ability, especially considering all of the touch screen tasks involved a motoric response. This corroborates previous research that has shown verbal processing speed measures to be predictive of mathematical ability in preterm populations (Mulder et al., 2010), and suggests that processing speed might be a domain general predictor of early mathematical ability across cultures.

Finally, for the UK sample, good concurrent criterion validity was shown. As predicted, the new touch screen assessments of spatial intelligence and working memory correlated significantly with Block Design from the WPPSI-III. Likewise, the new touch screen assessments of manual processing speed, short-term memory and working memory correlated with Symbol Search from WPPSI-III.

Overall, these results demonstrate a valuable first step in the development of a cross-cultural touch screen assessment tool for measuring core cognitive and motor skills in primary school children. However, it is important to acknowledge that many of the correlations reported here are weak to moderate in strength, indicating that whilst initial "proof of concept" has been demonstrated, further refinement of the tasks included in this new touch screen assessment tool is needed. Despite these limitations, we have shown that using tablet technology with simple tasks that employ basic stimuli can address several of the challenges that arise in cross-cultural comparisons of child development. For example, with the new touch screen assessment tool, children are exposed to the exactly the same standardized procedures and protocols, and task instructions are given in the child's first language, thus eliminating bias induced through different assessors (Sabanathan et al., 2015), and the need for trained assessors, which in low-income countries are in very short supply. This means that the new touch screen assessment tool is easy to implement by educational staff with limited experience of standardized assessments. We have also shown that group administration is possible with tablet technology, thus reducing the time and human resources required for one-to-one administration of more traditional standardized tasks. In turn, assessments using touch screen tablet technology could become valuable and efficient tools for evaluating core cognitive and fine motor skills in primary school children that can be administered quickly, to groups of children, by class teachers.

Assessment delivery in the child's first language also addresses potential methods and item bias. The importance of the child's first language in assessments and education is widely emphasized (e.g., GEM Report, 2016) as less variance arises in academic performance if children are assessed in their first, rather than second, language (Pretorius and Mampuru, 2007). The new touch screen assessment tool can be readily adapted to other languages, as the task instructions are simple, the task stimuli comprise of basic shapes, and a virtual instructor demonstrates tasks to the child. These features make the new touch screen assessment tool suitable for use in different educational contexts and cultures.

Interestingly, potential differences in exposure to touch screen tablet technology across children in the two countries where the new assessment tool was piloted did not appear to effect performance. Whilst 70% of UK children have access to touch screen technology at home (Ofcom, 2014[5]) and in school (Clarke, 2014) most children in Malawi have limited exposure to touch screen technology. Thus, the Malawi sample had reduced familiarity with the medium of delivery compared to the younger UK sample. Steps were taken to address this potential exposure bias through the inclusion of a pre-assessment task that aimed to familiarize children with the required drag and drop and tapping movements needed to complete the cognitive, motor and mathematics tasks. Our results showed similar patterns of performance across countries for the tasks included in the new tablet-based assessment, except for working memory, demonstrating that this technology can be used effectively to assess core cognitive and fine motor skills even in children with limited exposure to using touch screens.

Also, using stimuli that are simple geometric shapes rather than pictorial representations addresses problems highlighted in previous research that were limited by using culturally bound pictorial stimuli (e.g., Prado et al., 2010). Although it could be argued that geometric shapes are more familiar in high-income countries compared to the developing world (Roberson et al., 2002), basic geometric shapes and colors are represented in low-income countries, in both urban and rural environments. Mathematics is also one of the key "Learning Areas" in the national curriculum delivered in most low-income countries, such as Malawi (Chirwa and Naidoo, 2014), indicating that primary school children in low-income countries should have some experience of geometric shapes. The similar patterns of performance shown in our study across children from Malawi and the UK demonstrates the appropriateness of using basic shapes and colors for task stimuli in cross-cultural assessments of cognitive and motor skill.

For this new tablet-based assessment tool to be used to effectively to target individuals at risk of learning difficulties and in need of intervention, further development is needed in three key areas. Firstly, the current tasks require refinement to ensure the sensitivity of this new assessment tool to different ages and cultures. Results from the current study show age correlated with most of the tasks included in the new touch screen assessment tool, despite differences in the age range of the UK and Malawi samples. When the new touch screen assessment tool is highly sensitive to a broader range of ages than investigated here, this will enable the effects of maturation from schooling to be disentangled, as the age at which children start formal schooling differs across cultures. Criterion validity also needs to be evaluated in low-income countries. This may prove difficult, however, as, in many low-income countries there is no "gold standard" assessment for cognitive and motor assessments for children aged above 6 years on which to compare to this new touch screen assessment tool, so other approaches could be used that utilize three-dimensional local stimuli (Zuilkowski et al., 2016).

Secondly, the item battery should be expanded to include other domains, in particular, spoken and written language skills. Receptive and expressive language skills are vital for scholastic development and are key in the identification of learning difficulties, as language difficulties are widely associated with increased risk of poor educational outcomes (Tomblin, 2008; Peterson et al., 2009). For example, vocabulary knowledge is closely related to children's mathematics skills (Lee et al., 2004), and language proficiency is closely associated with academic attainment in the UK (Whiteside et al., 2016), and in low-income countries (Pretorius and Mampuru, 2007). Similarly, written language skills, especially literacy, are considered key building blocks on which later learning is dependent (e.g., Cunningham and Stanovich, 1997; Duncan et al., 2007; Sparks et al., 2014), so inclusion of tasks assessing spoken and written language processing would enhance the scope of this new cross-cultural touch screen assessment tool.

Finally, standardization is needed with the collection of normalized data across a large sample of pupils in low-to-high-income countries. This would afford comparisons between children's actual performance on the assessment tasks and their expected levels of performance based on developmental trajectories. This would aid in the identification of children in need of additional educational support and would enable the underlying nature of poor scholastic attainment to be investigated by profiling relative strengths and weakness in performance. For teachers to optimize the potential of this new cross-cultural assessment tool, guidance is required as to the interpretation of test performance and in how to scaffold individual learners identified at risk of underachievement and in need of intervention support.

CONCLUSION

The attainment of a child's full development capability is considered a human right by the United Nations (Convention on the Rights of the Child, 1989, article 6[6]) and the early identification of children with disability is a high priority (World Health Organization, 2012[7]). For the first time, we have demonstrated that touch screen tablet technology can address this concern by providing a reliable and valid method of assessing core cognitive and motor skills, known to be associated with scholastic progression, in the early primary school years. The advent of touch screen assessment tools to evaluate early child development, such as the one described here, is important as this new technology will enable strengths and weaknesses of individual children to be determined, which will inform educators of those children most at risk of learning difficulties.

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This, in turn, will help to target educational interventions to those most in need, assuring no child is left behind. In addition, our touch screen assessment tool has been shown to be applicable across low- and high-income countries so it can be used to make cross-cultural comparisons of early child development. This will enhance theoretical understanding of generic factors and culturally-specific factors that are required for progress through school, especially for children at risk of learning difficulties, and will enable educational interventions to be evaluated at a global scale.

AUTHOR CONTRIBUTIONS

NP designed the new touch screen tablet-based assessment and conducted Study 1. LO conducted Study 2 and analyzed both datasets. Both authors co-wrote the manuscript.

FUNDING

The manuscript was prepared, in part, during the award of an ESRC-funded PhD Studentship (ES/J500100/1) to LO.

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Conflict of Interest Statement: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

frontiers in Psychology

ORIGINAL RESEARCH
published: 25 October 2016
doi: 10.3389/fpsyg.2016.01603

Children Can Learn New Facts Equally Well From Interactive Media Versus Face to Face Instruction

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Today's children have more opportunities than ever before to learn from interactive technology, yet experimental research assessing the efficacy of children's learning from interactive media in comparison to traditional learning approaches is still quite scarce. Moreover, little work has examined the efficacy of using touch-screen devices for research purposes. The current study compared children's rate of learning factual information about animals during a face-to-face instruction from an adult female researcher versus an analogous instruction from an interactive device. Eighty-six children ages 4 through 8 years (64% male) completed the learning task in either the Face-to-Face condition ($n = 43$) or the Interactive Media condition ($n = 43$). In the Learning Phase of the experiment, which was presented as a game, children were taught novel facts about animals without being told that their memory of the facts would be tested. The facts were taught to the children either by an adult female researcher (Face-to-Face condition) or from a pre-recorded female voice represented by a cartoon Llama (Interactive Media condition). In the Testing Phase of the experiment that immediately followed, children's memory for the taught facts was tested using a 4-option forced-choice paradigm. Children's rate of learning was significantly above chance in both conditions and a comparison of the rates of learning across the two conditions revealed no significant differences. Learning significantly improved from age 4 to age 8, however, even the preschool-aged children performed significantly above chance, and their performance did not differ between conditions. These results suggest that, interactive media can be equally as effective as one-on-one instruction, at least under certain conditions. Moreover, these results offer support for the validity of using interactive technology to collect data for research purposes. We discuss the implications of these results for children's learning from interactive media, parental attitudes about interactive technology, and research methods.

Keywords: child development, children's learning, interactive technology, learning and memory, cognitive development, early childhood education, research methods

OPEN ACCESS

Edited by:
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Swinburne University of Technology, Australia

Reviewed by:
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Specialty section:
This article was submitted to Developmental Psychology, a section of the journal Frontiers in Psychology

Received: *16 June 2016*
Accepted: *03 October 2016*
Published: *25 October 2016*

Citation:
Kwok K, Ghrear S, Li V, Haddock T, Coleman P and Birch SAJ (2016) Children Can Learn New Facts Equally Well From Interactive Media Versus Face to Face Instruction. Front. Psychol. 7:1603. doi: 10.3389/fpsyg.2016.01603

INTRODUCTION

It is staggering to imagine that there are as many mobile devices in use today as there are people in the world. There are over 9.6 billion devices in use today versus 7.4 billion people currently on Earth (Radicati, 2014). Moreover, projections suggest that by the end of 2018 the number of worldwide mobile users is expected to surpass 6.2 billion. That is, roughly 84% of the world's population will be using mobile technology by year-end 2018 (Radicati, 2014). The recent rise in the use of mobile devices is also reflected in the fact that in many developed countries the majority of parents allow their children to use them at home (e.g., Beauchamp and Hillier, 2014). Indeed, the Rideout et al. (2003) reported that, even at that time, nearly 48% of US children 6 years of age had used a computer and more than 30% had also played video games. Remarkably, US children 6 years of age and under spent, on average, the same amount of time with screen media per day (1 h, 58 min) as they did playing outside (2 h, 1 min; Rideout et al., 2003).

Due to the increasing use of mobile devices at home there has been an explosion in electronic media directly targeting young children. Apple Inc., for instance, has recognized children's increasing mobile device use in their launch of a Kids App Store. The creation of this new category acknowledges children's interest in using apps and recognizes that children make up a substantial portion of app users. In fact, children are the targets of over 80% of the top selling paid apps in the education category of the iTunes store (Shuler, 2012).

Despite the rapid growth in children's use of interactive technology, research comparing the efficacy of children's learning from interactive media versus more traditional learning contexts is still relatively scarce. The primary goal of the research presented here is to help fill that gap by experimentally comparing how well preschool-age and early school-age children learn new facts from interactive technology versus from a face-to-face interaction with an adult. In the current literature, there are studies that compare children's learning between live interactions and video (e.g., Reiser et al., 1984; Kuhl et al., 2003; Krcmar et al., 2007; Roseberry et al., 2010) and between live interactions, video chat, and video (e.g., Roseberry et al., 2014), with results suggesting that children do not learn some types of information (e.g., language input) from TV or videos as well as they do from live interactions. For instance, research by Patricia Kuhl and her colleagues (Kuhl et al., 2003) found that between 9 and 10 months of age infants show phonetic learning from live, but not prerecorded, exposure to a foreign language. The results of this study suggest a learning process that is enhanced by social (face-to-face) interactions. On the other hand, results from a meta-analysis suggest that individuals in online learning conditions (e.g., print-based correspondence education, broadcast TV or radio, videoconferencing, stand-alone educational software) performed *better* than those receiving face-to-face instruction (e.g., in-person lectures, holding meetings with groups of students), with the important caveat that this meta-analyses included much older participants (i.e., Kindergarten through grade 12) and a variety of different learning mediums (Means et al., 2009).

Critically, empirical research on how *interactive* touch-screen devices affect learning outcomes remains extremely scarce (see Haßler et al., 2015; Radesky et al., 2015). A handful of recent studies have shown the positive effects of touch-screen mobile devices on children's learning in a few domains. For example, Neumann (2016) found evidence to suggest a positive association between 2- to 4-year-olds' use of touch-screen devices and their print awareness, print knowledge, and sound knowledge, suggesting that these pre-writing activities can promote the development of reading and writing skills. The use of an iPad also allows 2- to 3-year-old children to produce more continuous and complex mark making (a foundational skill for writing) when compared to the use of traditional paper and paint (Price et al., 2015). Importantly, touch-screen devices have also been shown to allow learning to transfer from the device to a physical version of a similar task (i.e., puzzles) (Huber et al., 2016). These aforementioned studies on the effects of interactive media on learning have focused on what children can learn from such devices *on their own*. However, it is important to recognize that children often engage with interactive media in a social context (e.g., in the presence of a caregiver or peer) that can influence learning. For example, research by McPake et al. (2013) showed that touch-screen devices have the potential to facilitate communicative and creative skills when the child observes an adult using that technology before trying it out on their own. It also appears that there are strategies that parents can use to enhance children's learning when using interactive media. Research by Flynn and Richert (2015) showed that using novel interactive media allowed children to perform better on letter and number recognition and device knowledge when parents focused on the content of what was being learned, rather than focusing on the device itself. Therefore, when evaluating the efficacy of any learning approach it is important to consider the broader social context, including the level of parental and teacher involvement as well as the parents' and teacher's beliefs about its efficacy.

If you look at how pervasive interactive media is today in both the home and the classroom it is tempting to assume that many parents and educators believe they are effective learning tools. For example, even parents of children between the ages of 6 and 24 months report they frequently give their children a mobile device to play with (see Bedford et al., 2016; Wooldridge, 2016). Unfortunately, when asked about their reasons for giving such devices to their children, parents' top three reasons did not include teaching and learning, but instead were to 'entertain,' 'videochat,' or 'calm their children' (Wooldridge, 2016). Similarly, a study by Beauchamp and Hillier (2014) reported that the most popular reason parents gave for using interactive tablets with their children was for entertainment purposes, whereas only 19% reported using them for their children's learning. Yet, the same report revealed that 83% of these parents believed that technology is important to their child's success in school (Beauchamp and Hillier, 2014). Parental attitudes toward interactive technology suggest that they believe their value lies primarily in entertainment, rather than in its educational potential. Indeed, a majority of parents believe that any learning from touch-screen devices is inferior to that acquired through real-world experiences and interactions (Wooldridge, 2016)[1]. Are parents' concerns about the educational value of such devices justified? Or, are they simply due to a lack of evidence on the positive benefits of learning from interactive devices?

Despite the scarcity of rigorous experimental research on learning from interactive media, the market for children's

[1] Interestingly, one might expect that these parents would be reluctant to allow their child to use such devices, yet there is no correlation between negative parental attitudes about interactive technology and their reports of their child's use of touch-screen devices (Wooldridge, 2016).

educational apps continues to grow, and for seemingly good reasons. On its face, interactive media has significant advantages over traditional toys and over other forms of media such as television or video including reactivity, interactivity, tailor-ability, progressiveness (i.e., the ability to become increasingly more challenging over time), and portability (Christakis, 2014). For instance, interactive screens are predetermined (like a video) but still reactive to the child's actions (like a socially contingent interaction). In addition, the mobility of devices allows learning to happen anytime and anywhere. The student is no longer restricted to having to sit in a single location in front of a computer to use technology in an educational context. This accessibility and portability allows parents to introduce technology as a part of their child's education at a very young age, and easily supplement learning outside of the typical classroom environment or person-to-person instruction.

As parents and teachers continue to incorporate mobile devices in children's lives, the need for studying the effects of mobile interactive media in children's learning becomes increasingly valuable. A study examining the prevalence of iPads in the classroom setting, for instance, found that early childhood educators across all programs and student income levels reported almost a twofold increase in tablet access from 2012 to 2014 (Blackwell, 2015). The American Academy of Pediatrics (2013) has updated their views to acknowledge the value of educational media in young children's learning, and government agencies and school districts have committed large budgets to increase technology in classrooms. For example, Apple Inc. reported that there were over 10 million iPads in use in schools around the world as of 2013 (Apple.com, 2016). Yet, in a systematic review on how the use of interactive tablets affects learning outcomes among children, Haßler et al. (2015) concluded that policies established on the use of interactive tablets in children's learning are based on little evidence, and highlight the need for more rigorous studies to understand how interactive tablets affect children's learning.

In the current experiment, we compared children's rate of learning (i.e., how much participants learned) during a face-to-face (one-on-one) instruction with a female adult versus their rate of learning from an interactive iPad application in the presence of a female adult. Our aim was to quantify and compare the amount of learning taking place between the two learning contexts, as well as to validate the use of interactive media as a means of collecting data from children for research purposes. In both the 'Face-to-Face' and 'Interactive Media' conditions, which were presented as games, children were taught new facts about animals. The procedures were analogous except that in the Face-to-Face condition a female adult instructor taught the child facts using printed visual aids (e.g., animal pictures), whereas in the Interactive Media condition the same information was presented on a touch-screen tablet accompanied by pre-recorded audio files of an adult female voice represented by a cartoon character. To examine the effects of interactive media on factual learning in early childhood, children 4 to 8 years of age were tested. A wealth of previous research has demonstrated that children's learning and memory tends to improve with age (e.g., Gathercole et al., 2004; Hala et al., 2013). Given this, and the fact that this age range includes preschool-age children (ages 4 and 5) who spend most of their time in informal learning contexts (e.g., home, daycare, kindergarten) as well as school-age children (ages 6+) who have been exposed to more formal and structured learning contexts (e.g., classroom settings), we also examined age-related changes in children's learning across the two conditions.

MATERIALS AND METHODS

Participants

Eighty-six children between 4 and 8 years of age participated in this study. Forty-three children ($M = 67.30$ months, $SD = 13.29$; 15 females) participated in the Face-to-Face condition and were randomly assigned to learn animal facts in a specific order (out of four possible orders, or versions, described below). An additional 43 children ($M = 66.56$ months, $SD = 12.68$ months; 17 females) participated in the Interactive Media condition. To equate the two groups for age and order, a commonly used 'matching' technique was applied such that each participant in the Interactive Media condition was 'matched' with a previous participant from the Face-to-Face condition by selecting the participant closest to that individual in age (to the nearest month), and assigning that participant to the same order. This study was approved by, and carried out in accordance with the ethical standards of, the University of British Columbia's Behavioral Research and Ethics Board with written informed parental consent for all subjects.

Children in both conditions were tested in a quiet setting in a child development lab, science museum, local preschool, or park setting. Ethnic demographics were similar in both the Face-to-Face (41.9% White, 18.6% East Asian, 11.6% South Asian, 20.9% Other) and Interactive Media (51.2% White, 16.3% East Asian, 4.7% South Asian, 14.0% Other) conditions. Nine additional children were tested, but their data were not included in the analyses: 3 due to a failure to complete the task and 6 due to experimenter error or technological problems.

Materials

Learning and Testing Materials

Two sets of four trivia questions (Set A and Set B; see **Table 1** for a complete list of questions) were used in this experiment. Each child was taught the answers to one set of questions, but not the other. The 'untaught' questions served as a baseline measure of question difficulty and ensured that children of this age did not know the answers to these facts beforehand. We varied whether children were taught Set A questions or Set B questions as well as which set of questions came first, resulting in four possible orders or versions (i.e., Set A first and Set A taught, Set B first and Set B taught, Set A first and Set A untaught, and Set B first and Set B untaught). Participants in the Face-to-Face condition were assigned to one of the four possible versions at random. Each participant in the Interactive Media condition was assigned the version that corresponded with their closest age 'match' from the Face-to-Face condition to equate the groups for age, question set, and question order.

TABLE 1 | List of factual questions and four possible response options used during the testing phase.

Question Set	Question	Option 1	Option 2	Option 3	Option 4
A	Which kind of insect, or bug, is the smallest?	**Fairyfly**	Leaf beetle	Lady bug	Seed bug
	Which kind of bear is the largest?	Grizzly bear	**Polar bear**	Black bear	Panda bear
	Which kind of dog cannot swim?	Pug	Brussels griffon	Poodle	**Basset hound**
	Which animal is the best jumper?	**Flea**	Goat	Grasshopper	Rabbit
B	Which kind of bird can fly the highest?	Peregrine falcon	Malleefowl	**Ruppell's vulture**	Eagle
	Which part of the body is called the nape?	Bottom of the feet	Back of the knees	**Back of the neck**	Top of the head
	Which animal is the fastest in the sea?	Clownfish	**Sailfish**	Pilot whale	Mako shark
	Which animal has the best hearing?	Elephant	Bat	Three-toed sloth	**The Greater Wax Moth**

*Correct answers are indicated in bold text. When children were asked to choose between the four responses option, they were presented with four pictures displaying each option; none of these images were displayed during the learning phase. The position of the pictures is reflected in the table, such that Option 1 was presented in the top left quadrant, Option 2 in the top right quadrant, Option 3 in the bottom left quadrant, and Option 4 in the bottom right quadrant (see **Figure 2** for a sample).*

Visual Aids and Equipment

Each question and response option was accompanied by images as visual aids. All images in this study were publicly sourced and labeled for reuse. For the Face-to-Face condition, the images were printed out and shown by the experimenter (one of eight adult female research assistants). For the Interactive Media condition, an iPad app was developed in Swift 2.0 featuring a cartoon figure (Laila the Llama) that narrated the app, replacing the role of the live instructor (see **Figure 1**). The app was presented using an iPad Pro. The same images used in the Face-to-Face condition were used in the Interactive Media condition (see **Figure 1** for a sample). Audio recordings of the instructions, questions, and response options were recorded for the app using an adult female's voice (a different voice from the 8 female research assistants; one of whom was always present during the experiment). A full version of the interactive media app is available on-line: http://tinyurl.com/jzk5mym.

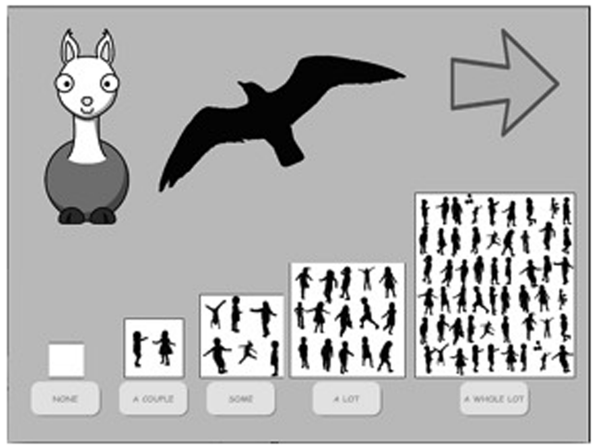

FIGURE 1 | Sample screen presented to children in the Interactive Media condition featuring a cartoon, Laila the Llama, that taught the children facts using a corresponding pre-recorded female voice. The recordings were triggered by the child's responses or by the lapse of a preset amount of time in such a way that they appeared 'socially contingent' with the child.

Procedure

Each child was tested individually in the presence of an adult female research assistant. The procedure, which was presented as a game, took place in three main phases: A Demonstration Phase, A Learning Phase, and a forced-choice Testing Phase. Prior to the Demonstration Phase, the research assistant introduced herself to the child and asked if the child would like to play a game. In the Interactive Media condition, the female researcher subsequently activated the app wherein the cartoon llama introduced herself saying, "Hi, I'm Laila the Llama! Would you like to play a game with me?" via the prerecorded audio files.

Demonstration Phase

If children agreed to participate in the game, the research assistant (in the Face-to-Face condition) and Laila the Llama (in the Interactive Media condition) demonstrated how to play the game, saying, "Let me show you how to play. See this board? There's no children here, there's a couple of children here, there's some here, a lot here, and there's a whole lot of children here! I am going to ask you some questions and you can show me how many children your age will know the right answer by pointing to one of these." (See **Figure 1**). The demonstration continued with the interactive tutorial or the live instructor providing three sample questions and answers (e.g., "A cow says moo. How many children your age will know that? I think a whole lot of children will know that so you'd point here." (i.e., point 5 on the scale). This process was repeated two more times to illustrate a much more difficult question and a question of medium difficulty (Refer to Appendix A for a detailed description of the full Demonstration Phase). This phase lasted approximately 2—3 min.

Learning Phase

During the Learning Phase, children were presented with the eight trivia questions each accompanied with an 'anchor' image. For example, children were presented with a question about which bird can fly the highest and the accompanying anchor image was a silhouette of a bird. These anchor images were presented again later when the same question was asked during the Testing Phase. For half the trials, children were taught the answers to one set of questions (e.g., they were taught Set A), whereas they were not taught the answers to the other set of questions (e.g., they were not taught Set B). In each learning trial, the new facts were embedded in the question of how many of their peers would know the answer. This 'guessing game-like' learning context was intended to create a naturalistic learning situation that was engaging, but not anxiety-provoking or overly formal, and as such children were not told this was a teaching lesson or that their memory for the facts would be tested.

For each taught trial, children heard the new fact, followed by the question, "How many children your age will know [question]?". For instance, "The Ruppell's vulture is the bird that can fly the highest. How many children your age will know which bird can fly the highest?". For each untaught trial, children simply heard the question, "How many children your age will know [question]?" and were not provided with the answer. For example, they heard, "How many children your age will know which bird can fly the highest?"[2]. Children answered these questions by tapping on, or pointing to, one of the five buttons illustrating a different number of peers on a five-point scale (described in Appendix A in the Supplemental Materials; see also **Figure 1**). Children could also have the question repeated[3]. In the Face-to-Face condition, the instructor asked children if they would like to have the question repeated, whereas in the Interactive Media condition the Llama instructed them on how to hear the question again (e.g., "tap on me" to hear the question again). This phase lasted approximately 4 min.

Testing Phase

During the Testing Phase, children were presented with all eight trivia questions again in the same order as they were presented during the Learning Phase. In the testing phase, the questions were presented in a multiple-choice format with four options surrounding the 'anchor' images (refer to **Figure 2** for a sample and **Table 1** for the placement of the correct answers). The location for the correct answer was predetermined by pseudo random order but was fixed for all children.

The testing phase occurred without delay after the Learning Phase in the Face-to-Face condition. The Interactive Media condition began with an interactive tutorial, lasting 30 s, where Laila the Llama explained how to choose their answers using the pre-set response options and prompted children to do one practice trial (e.g. "What animal says moo? Is it a cow, a chicken, a pig, or a horse?") while the pointer finger moved along with the audio to direct attention to the corresponding image. Importantly, the animations of the images were synced to the timing of the audio so that the audio labeled the images as they appeared; after appearing, the images were grayed out to indicate the inability to interact with the screen until the children had seen and heard all the options. The subject was prompted to tap on an image and the app waited until this action was completed before surfacing the green arrow to allow the child to move on when ready.

During test, the instructor (i.e., the female adult or Laila the Llama) asked each child the trivia questions, and presented the four options by pointing to each image and labeling it (e.g., a Peregrine falcon, a Malleefowl, a Ruppell's vulture, or an Eagle). In the Interactive Media condition this was done through an audio recording of each question and its four options. The children indicated their responses by pointing or tapping on the intended image. Once again, children were able to get the question repeated during this Testing Phase by either asking the instructor (Face-to-Face condition) or tapping on the center 'anchor' image (Interactive Media condition). If a child requested a question repeat in the Interactive Media condition, all elements on the screen disappeared and re-entered in the same manner as before. The latter feature was limited to three repeats. After the eight trivia questions, the instructor thanked the child for playing the game and presented him or her with four stars. In the Face-to-Face condition, the stars were stickers (that the child kept), and in the Interactive Media condition, the stars were presented on the screen.

RESULTS

Children's rate of learning across the two conditions was determined by computing the total number of taught trials (out of 4) in which they chose the correct answer. These totals served as our dependent variable.

Preliminary Analyses

We first ruled out any order effects (i.e., which set was taught, Set A or Set B, and which set came first, Set A or Set B), $ps > 0.10$. To additionally rule out gender effects, we tested whether children showed a higher rate of learning in the Face-to-Face condition compared to the Interactive Media condition using a 2×2 ANOVA with gender and condition as between-subjects factors. No differences by gender were obtained, $F(1,84) = 0.011$, $p = 0.915$; therefore the remainder of the analyses collapse across gender and order.

Primary Analyses

Children learned equally well from the interactive iPad app ($M = 1.86$ of four items) as they did from a live instructor [$M = 2.12$ items, $t(84) = 0.907$, $p = 0.564$, two-tailed, $d = 0.2$]. That is, children showed similar learning performance on this task regardless of whether they learned the facts from a female adult during an in-person interactive learning exercise or from an analogous learning exercise developed for the iPad. On average, children remembered approximately 2 of the 4 new facts that were introduced. Although their performance was not near ceiling, it significantly exceeded chance (25% or 1 of 4 items) in both the Face-to-Face, $t(42) = 5.357$, $p < 0.001$, two-tailed, $d = 0.82$, and Interactive Media, $t(42) = 4.530$, $p < 0.001$, two-tailed, $d = 0.69$, conditions.

Importantly, as a comparison, children performed below chance for the questions about facts that they were not taught, in

[2]These data (i.e., children's answers to "how many children will know [question]?") were analyzed for separate research purposes and were not included in this manuscript.

[3]The facts were repeated more often in the Face-to-Face condition than in the Interactive Media condition making the equivalent rates of learning across the two conditions possibly even more compelling. However, children's requests to have the question or the fact repeated were quite rare occurring on less than 1% of all trials. The trials that children requested to have repeated most often corresponded with the answers: 'Ruppell's Vulture' and 'the Greater Wax Moth' (tied for the most repeats), followed by the 'Fairyfly' and 'Back of the neck' (tied for second).

FIGURE 2 | A sample of the anchor picture (the silhouette of a bear) surrounded by four potential response options. Children were asked to tap their answer (Interactive Media condition) or point to their response (Face-to-Face condition).

both the Face-to-Face [$M = 0.65$, $t(42) = -3.041$, $p = 0.004$, two-tailed, $d = -0.93$] and Interactive Media conditions [$M = 0.77$, $t(42) = -2.031$, $p = 0.049$, two-tailed, $d = 0.63$]. The majority of children's incorrect answers in this case reflected responses they were more familiar with. For instance, the majority of the children who were not taught the question, "Which kind of bird can fly the highest?" chose "eagle" as their answer, rather than the correct response "Ruppell's vulture". Thus, our interpretation is that the below chance performance for the untaught questions reflects the difficulty of the facts and children's tendency to select the most familiar answer as a response strategy when answering questions for which they do not know the answers. Ultimately, the difference in the observed response patterns for taught versus untaught facts highlights the ability of both Face-to-Face and Interactive Media conditions to facilitate children's learning.

To test whether children's learning varied as a function of age, we examined the correlation between children's age in months and their memory for previously taught facts. Age was positively correlated with improved memory performance, $r = 0.341$, $n = 86$, $p = 0.001$. That is, as children got older they were more likely to learn or remember the facts they had been taught. This same developmental pattern of learning was observed in both the Face-to-Face, $r = 0.385$, $n = 43$, $p = 0.011$, and Interactive Media Conditions, $r = 0.289$, $n = 43$, $p = 0.061$. Our sample includes a group of children (Preschool Age: 4 and 5 year-olds) who do not yet spend the majority of their time in formal learning contexts and a group of children who have transitioned to elementary school where they are introduced to more formal and structured learning (School Age: ages 6+). Thus, to further examine potential age differences, we split participants into School Age (age > 72 month, $n = 30$) and Preschool categories (age < 72 months, $n = 56$) and conducted a 2 × 2 ANOVA with Age and Condition as the between-subjects factors. This analysis revealed a main effect of Age, $F(1,84) = 05.38$, $p = 0.023$, with School Age children performing better than Preschool Age children, but no main effect of Condition ($p = 0.481$) and no significant interaction, $p = 0.830$. Further analyses showed that children in both age categories remembered items at above chance rates (25% or 1 of 4 items): School Age, $t(29) = 5.787$, $p = 0.049$) and Preschool Age, $t(55) = 4.583$, $p < 0.001$ (See **Figure 3**).

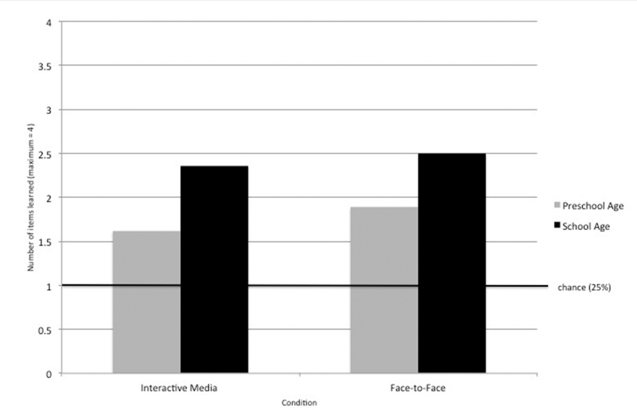

FIGURE 3 | Average number of items recalled (out of a total of 4) by Condition and Age Group. School aged children learned significantly more items than preschool aged children. Children in both age groups recalled items at significantly greater than chance rates (25% or 1 of 4 possible answers) and there were no differences by condition.

DISCUSSION

The primary goal of the present research was to compare 4- to 8-year-old children's rate of learning factual information in an experimental learning task presented by an adult instructor versus an interactive media device (i.e., a child-friendly app designed for the iPad). Our analyses revealed that children performed equally well in the Interactive Media condition as they did in the Face-to-Face condition. That is, the 4- to 8-year-old children in our sample recalled the facts they were taught at rates significantly above chance, regardless of whether they learned those facts from an adult researcher or via an interactive iPad app in the presence of an adult researcher.

Unsurprisingly, children's age in months was also positively correlated with their memory performance, which is consistent with a wealth of previous findings showing that children's learning and memory improves with age (see for e.g., Roberts and Blades, 2000; Gathercole et al., 2004; Ofen et al., 2007; Hala et al., 2013). Moreover, school-age children (ages 6 through 8) performed significantly better than preschool age children (ages 4 and 5). This same developmental pattern of learning was observed in both the Face-to-Face and Interactive Media Conditions. Importantly, however, even the preschool age children performed significantly above chance. These findings suggest that face-to-face instruction and interactive touch-screen applications can be similarly effective learning methods for children ages 4 through 8.

The current study contributes to our understanding of children's learning through interactive media, however, future research can further elucidate this process. For instance, the current study examined learning in a naturalistic, relatively informal, game-like setting where the children did not know in advance that they would be tested on the information presented. It is therefore a question for future research how interactive media compares to live instruction for more formal and explicit testing situations (e.g., where children are explicitly instructed to memorize new information for later testing). In addition, in our research the testing phase took place immediately following the learning phase. As such, it is an open question for future research whether interactive media and live instruction are equally effective for retaining newly acquired information for longer periods of time.

Given the increasingly prominent role technology is playing in children's lives, our findings make an important contribution to a small but growing body of literature on the comparative effectiveness of so-called 'digital learning' versus more naturalistic or traditional pedagogical approaches. Findings from the earlier literature were somewhat mixed on the efficacy of learning from digital media. As previously mentioned, a meta-analysis examining learners from kindergarten through high school found that students in online learning conditions (e.g., correspondence learning, stand-alone educational software, broadcast TV, or radio) performed better, on average, than those in more traditional face-to-face instruction (e.g., in-person lectures, student meetings; United States Department of Education, 2009). However, in other learning contexts children's learning is far inferior from digital media (e.g., TV) than it is from live social interactions (e.g., Kuhl et al., 2003). For instance, previous research suggests that 9 and 10 month olds show phonetic learning from live, but not prerecorded, exposure to a foreign language, and that children tend to imitate live demonstrations more than they imitate demonstrations from television, until at least 3 years of age (Zack et al., 2009).

The aforementioned *seemingly* mixed results highlight the importance of considering, and comparatively testing, the *type of media* that is used as well as the *type of learning* being tested, not to mention the age of the participants involved. Recent work by Bedford et al. (2016) made important strides in this regard. Using an online survey of 715 parents of 6- to 36-month-olds they examined how age of first touchscreen usage (retrospectively reported) related to gross motor (i.e., walking), fine motor (i.e., stacking blocks), and language (i.e., producing two-word utterances) milestones. Their results revealed that for toddlers, aged 19—36 months, age of first touchscreen use was significantly associated with fine motor skills (stacking blocks) after controlling for age, sex, mother's education (a proxy for SES), and the age at which they achieved a fine motor milestone (pincer grip). Importantly, this effect was only present for active scrolling of the touchscreen and not for passively observing the device (e.g., video watching). No significant relationships were found between touchscreen use and either gross motor or language milestones. These data provide converging evidence with other work suggesting the potential power of digital tools to facilitate learning such as letter and number recognition (Flynn and Richert, 2015) and knowledge transfer from media learning to analogous physical problems (Huber et al., 2016; see also Semmelmann et al., 2016).

Similarly, a report by Radesky et al. (2015) reviews the limited research on the impact of interactive media use on children and suggests that interactive media can be useful for teaching concrete knowledge (e.g., science, addition, subtraction, counting, multiplication, and chemistry); however, skills such as self-regulation and empathy are perhaps best learned through interactions with peers and caregivers in naturalistic environments. Much more work is needed to investigate whether face-to-face instruction and interactive media methods are equally effective at teaching different types of information (e.g., trivia facts versus procedural information such as how to fold a flag or pitch a tent) and different kinds of skills (e.g., cognitive vs. social skills). Radesky et al. (2015) also acknowledged that interactive media can promote learning by demonstrating ideas for parent—child activities, or by modeling teaching strategies (e.g., dialogic reading, phonetic, or sound blending skills).

As mentioned in the introduction, many parents and educators hold negative attitudes toward interactive devices for learning purposes compared to the perceived benefits of 'real-world' learning opportunities (Wooldridge, 2016). These perceptions might lead some individuals to expect superior learning in the Face-to-Face condition. In contrast, our finding suggests that perhaps caregivers and educators do not need to be overly concerned about the use of technology for learning, given that interactive media appears equally effective as face-to-face instruction, at least for certain learning contexts (e.g., the factual learning tested in the present research). Of course, the potential benefits of children's use of interactive technology will ultimately depend on what children are doing on the interactive device (e.g., whether the apps being used include an educational component—intentionally or otherwise).

Importantly, although facts taught in the Interactive Media condition came from a pre-recorded (albeit programmed to be interactive) voice as opposed to a live instructor in the Face-to-Face condition, an adult research assistant was always present with the child during testing and watched the child interact with the iPad game. Although the researcher did not by default say anything during the child's interaction with the iPad, if the child got distracted she encouraged the children to keep playing, or if the child was very delayed in responding she reminded the child that they could tap on the llama to hear the question again (akin to the same kinds of encouragement offered in the Face-to-Face condition). These conditions arguably provided some social scaffolding and may have included important attentional or pedagogical cues that facilitated learning. Consistent with this notion, previous work has demonstrated that even at 12 and 15 months of age, word learning is not facilitated by repeated viewings of educational DVDs (i.e., Baby Einstein) (Robb et al., 2009). However, watching similar programs (i.e., Baby Mozart) alongside a caregiver, who scaffolded their viewing behavior and increased shared attention and turn-taking, was associated with better responsiveness and attention to the learning source (Barr et al., 2008; Fidler et al., 2010).

Similarly, although some research suggests that until around age 3 children have difficulty transferring '2D learning' into the real 3D world; a so-called 'video deficit' (see Anderson and Pempek, 2005 for a review), contingent engagement helps children successfully transfer this knowledge. For instance, children who had difficulty finding a toy hidden in a room if they watched the toy being hidden in a pre-recorded video, were able to find the toy if the experimenter interacted with the child, over video, throughout the hiding episode (Troseth et al., 2006). Other work on knowledge transfer has examined infants' ability to learn new words from screens and use them in real life, showing that by 24 months children learn the meanings of new words equally well in a live interaction and live video interaction, but not using pre-recorded non-interactive video (Roseberry et al., 2014). In other recent work, 104 parent–child dyads were videotaped using a touchscreen tablet to observe the supports and exchanges between parent and children ages 46–76 months. The results indicated that parents provided a great deal of support to their children while interacting with the touchscreen tablet including verbal, physical, and emotional support. The type of support offered did not differ as a function of parent gender or experience with mobile devices (users versus non-users) (Wood et al., 2016). Together, these results underscore the important role that a physically present and supportive adult may play in our results as well as in the broader literature. It is an open question whether the benefits of having some degree of social scaffolding during learning from interactive technology is similar to the benefits observed from social scaffolding when learning from more traditional '3D' toys or reading books. Future work that compares in-person to digital learning should consider the potential influence of the presence or absence of such social factors during learning (see Lovato and Waxman, 2016 for review).

Finally, in addition to their contribution to the literature on children's learning, our results offer much-needed empirical support for the validity of using interactive media for research purposes. We found that children ages 4 through 8 did not find it difficult to interact with the iPad. Moreover, given that children's performance was comparable to an analogous 'live' experiment, this research suggests that interactive technology may be an appropriate method to collect data to test research questions on a range of topics within developmental science, not just for research evaluating the efficacy of children's learning from interactive media. In fact, there were some clear benefits of using the interactive device over a live interaction for research purposes. For instance, the use of a pre-recorded tutorial insured that all participants experienced the exact same instructions using the same rate of speech and the same vocal intonations that is not possible when using live researchers. Computerized data collection methods also simplify data coding and data entry as responses and response times are automatically recorded, bypassing the need for more time-consuming coding of videotaped responses and the need for inter-rater reliability. Moreover, computerized data collection reduces the possibility of human error in inputting responses and eliminates the possibility of experimenter bias.

In sum, our results demonstrate that children 4 to 8 years of age learned factual information about animals equally well from an interactive iPad application as they did during face-to-face instruction. These results contribute much-needed data to the limited experimental evidence supporting the use of interactive media in children's learning. These data may help alleviate the concerns of some parents and educators who believe that learning from interactive media is inferior to learning from real-life interactions. Of course, interactive media should never, and could never, replace the many benefits of real-world social interactions but can be used in moderation to supplement real-world learning. Indeed, as parents gain confidence in the educational value of interactive media they may change their assessment of its primary value from 'entertainment purposes' to 'educational purposes'. Continued research in this field will have important implications for children's learning and education, parents' and educators' attitudes about interactive technology, and research methodology.

AUTHOR CONTRIBUTIONS

SB and SG designed the study. KK designed the iPad app and wrote the first draft of the Introduction and Methods. PC developed the back-end data collection platform and assisted with application development. SG, TH, and VL assisted with data collection. VL analyzed the data and wrote the first draft of the Section "Results". SB oversaw all aspects of the research. All authors contributed to the writing of the final manuscript.

FUNDING

This research was funded by a research grant from the Social Sciences and Humanities Research Council of Canada to the senior author SB.

SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: http://journal.frontiersin.org/article/10.3389/fpsyg.2016.01603

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Conflict of Interest Statement: SB is the founder of the company, Applied Cognition Corp., that helped fund the development of the free iPad learning app used in the experiment presented in this manuscript. All the other authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

frontiers in Psychology

ORIGINAL RESEARCH
published: 22 September 2016
doi: 10.3389/fpsyg.2016.01431

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Just Google It: Young Children's Preferences for Touchscreens versus Books in Hypothetical Learning Tasks

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Children today regularly interact with touchscreen devices (Rideout, 2013) and thousands of "educational" mobile applications are marketed to them (Shuler, 2012). Understanding children's own ideas about optimal learning has important implications for education, which is being transformed by electronic mobile devices, yet we know little about how children think about such devices, including what children think touchscreens are useful for. Based on a prior result that children prefer a book over a touchscreen for learning about dogs, the present study explored how children view touchscreens versus books for learning an array of different types of information. Seventy children ages 3–6 were presented with six different topics (cooking, today's weather, trees, vacuums, Virginia, and yesterday's football game) and chose whether a book or a touchscreen device would be best to use to learn about each topic. Some of this information was time-sensitive, like the current weather; we predicted that children would prefer a touchscreen for time-sensitive information. In addition, each child's parent was surveyed about the child's use of books and touchscreens for educational purposes, both at home and in school. Results indicated that younger children had no preference between books and touchscreen devices across learning tasks. However, 6-year-olds were significantly more likely to choose the touchscreen for several topics. Surprisingly, 6-year-olds chose a touchscreen device to learn about time-sensitive weather conditions, but not yesterday's football. Children's choices were not associated with their use of books and touchscreens at home and school.

Keywords: learning, touchscreen devices, educational tools, books, children's education

OPEN ACCESS

Edited by:
Gabrielle Strouse, University of South Dakota, USA

Reviewed by:
Nancy M. Wyss, Richard J. Daley College, USA
Kate Highfield, Charles Sturt University, Australia

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Specialty section:
This article was submitted to Developmental Psychology, a section of the journal Frontiers in Psychology

Received: *01 June 2016*
Accepted: *07 September 2016*
Published: *22 September 2016*

Citation:
Eisen S and Lillard AS (2016) Just Google It: Young Children's Preferences for Touchscreens versus Books in Hypothetical Learning Tasks. Front. Psychol. 7:1431. doi: 10.3389/fpsyg.2016.01431

INTRODUCTION

Children's use of touchscreen devices has grown tremendously in the last decade. In a 2013 nationwide survey by Common Sense Media, 72% of children below the age of eight used a mobile device – almost twice as many as in 2011 (Rideout, 2011, 2013). Although considerable attention has been paid to the "digital divide" between the technology access of lower- and higher-income families (e.g., Attewell, 2001; Wartella et al., 2013), recent research suggests that mobile use in low-income families is robust (Kabali et al., 2015). Kabali et al. (2015) surveyed an urban, low-income, minority community and found that 96.6% of children under the age of four had used mobile devices. Even by the age of two, over 75% of low-income children used mobile devices on a daily basis, more than four times the 17% rate reported by Common Sense Media two years prior (Rideout, 2013).

Children use mobile devices to watch videos, to play games, to read, to communicate with others, and increasingly, to learn. Educational applications abound in the touchscreen app marketplace and the majority are marketed toward children and teenagers (Shuler, 2012). Yet as recent reviews have highlighted, a severe lack of regulation hinders the ability of parents to choose educational apps wisely (Guernsey et al., 2012; Hirsh-Pasek et al., 2015). Parents hold varying attitudes about the educational benefits of media use. For example, 37% of parents claim mobile devices have a positive effect on their child's reading skills, while 21% claim a negative effect, and 40% claim a neutral effect (Wartella et al., 2013). The majority of parents of children under the age of eight are likely to use a book instead of a technological tool to educate their children, although this varies with age: 64% of parents with 6–8-year-old children say they would direct their child to a computer in order to learn (Wartella et al., 2013). Although 67% of parents claim books are very important sources of learning, only 44% claim interactive digital media are valuable for learning (Rideout, 2014). Parental attitudes toward media predict children's actual media use (Lauricella et al., 2015) and the extent to which parents view media as having educational value predicts their children's use of educational media tools (Cingel and Krcmar, 2013). Parents' own use also predicts their children's use, although parental attitudes toward media affect child use even when parents themselves are infrequent users (Lauricella et al., 2015). For instance, parents who have positive rather than negative attitudes toward tablets have children who spend more time with tablets, even if the parents are only low or medium tablet users. Thus, children's media use can be affected by both parental use and parental attitude, as well as by factors of age and availability (Lauricella et al., 2015; Rideout, 2011, 2013).

Increasingly, researchers are evaluating children's ability to learn from touchscreen devices and educational apps. In contrast to the literature on learning from television, which has consistently found that children fail to transfer information from screens to the real world (Barr and Hayne, 1999; Anderson and Pempek, 2005; Krcmar et al., 2007; Roseberry et al., 2009; DeLoache et al., 2010), studies examining learning from touchscreens have presented mixed results. Recent studies have shown that young children learned equally well from touchscreens and physical objects in a problem-solving task (Huber et al., 2015) and that nightly engagement with a math app increased children's math achievement, particularly for children whose parents were anxious about math (Berkowitz et al., 2015). Yet other studies indicate that young children have difficulty transferring between 2D touchscreens and 3D objects (Zack et al., 2009, 2013; Moser et al., 2015), presumably due to the challenge of extending new information beyond the specific context in which it was learned, though this may be most pronounced in infants (Barr, 2013). In a recent comparison of different learning tools, children learned geography better from a physical puzzle than an app version of the puzzle in an initial interaction with the tool (Eisen and Lillard, 2016). After children brought home either the puzzle or the app for 1 week, the degree of advantage was reduced and children who used the puzzle learned only marginally more than those who used the app; however, children used the app for twice as long as the puzzle over the week, suggesting that learning from the puzzle was more efficient. Further research on children's learning from touchscreen devices is greatly needed, especially considering how rapidly touchscreens have been integrated into classrooms across the country (Richtel, 2011).

One unexplored aspect of the topic is whether children view touchscreen devices as tools for learning. Children begin to discuss learning and teaching during the preschool years (Bartsch et al., 2003) and by the age of six they recognize that learning requires not just a desire to learn but attention to the task (Sobel et al., 2007). Yet when asked about new pieces of knowledge, preschoolers often claim they have always known the information (Taylor et al., 1994; Esbensen et al., 1997). Furthermore, 3-year-olds struggle to remember sources of learning, particularly after a delay (Gopnik and Graf, 1988), whereas 4- and 5-year-olds can remember sources but not when something was learned (Tang and Bartsch, 2012). By the age of four, children can generate details about how their own learning takes place (Bemis et al., 2011, 2013) but their ability to conceptualize and accurately describe learning develops well into the elementary school years (Sobel and Letourneau, 2015). In an open-ended interview, Sobel and Letourneau (2015) asked 4–10-year-old children about their concept of learning. Older children understood learning as process-based and gave answers that reflected learning strategies. In contrast, 4- and 5-year-old children often struggled to answer the questions, although approximately 40% described learning as a process by referring to either a source (such as a teacher) or a strategy (such as practice). Putting these findings together, it appears that by 4 years old, children's concept of learning in sufficiently developed to sensibly answer a question regarding the best source of learning.

To learn from a source, one must also evaluate that source as trustworthy and informative. This is just as true for technological sources as it is for social sources. Building off of the large literature on children's trust in human informants (e.g., Koenig et al., 2004; Jaswal and Neely, 2006; Birch et al., 2008), Danovitch and Alzahabi (2013) asked preschoolers to evaluate the accuracy of computer informants. Children as young as three showed selective trust in an accurate computer over an inaccurate computer. When asked to explain the errors of an inaccurate computer, 4- and 5-year-olds claimed the errors reflected the computer's lack of knowledge, not human error. This study indicates that young children understand that despite holding a wealth of information, computers are not infallible. Further research suggests that children initially trust human informants over technological informants, but by the age of five, children endorse technological over human informants (Noles et al., 2015). Adults favor technological informants as well, in both their endorsements and information seeking.

Relatedly, as children learn to read, they prioritize printed information over oral information (Einav et al., 2013; Eyden et al., 2013; Robinson et al., 2013). Early readers use printed labels to correct their own guesses and believe printed labels over oral labels (Robinson et al., 2013), even when the printed labels conflict with children's own impressions (Eyden et al., 2013). In contrast, pre-readers do not show the same affinity for print, although along with early readers, they may reject information that is printed but seems incorrect.

Do children recognize that touchscreen devices can be valuable sources of information? Eisen and Lillard (2015) showed preschoolers ages four to six images of various objects, including a book, iPad, and iPhone, and asked if the objects could be used to learn. Surprisingly, only 53.5% of children said that an iPad could be used for learning, and just 34.9% said an iPhone could be. In comparison, 81.4% of children said a book could be used for learning. Children were also asked to choose which object would be best for them to use for learning about dogs in a hypothetical scenario and the majority of children chose the book. These results indicate that children may privilege books over touchscreens in the context of learning, which is surprising given how attracted children can be to electronic devices. However, it is possible that when presented with an actual learning task using real objects, children would choose an electronic device over a book.

In the present study, children were offered a variety of topics to learn about and asked to choose between two potential learning tools: a book and a touchscreen. Eisen and Lillard (2015) found differences between smartphones and tablets in children's assessment of learning capacity, so we included both types of touchscreen to further explore these differences. Since Apple devices have dominated the touchscreen market for the last five years (King, 2015) and have been used in prior studies (Berkowitz et al., 2015; Huber et al., 2015), we used an iPad and an iPhone and referred to them by these names. The learning topics presented to children were chosen to cover a wide range of subjects that could be learned about in a variety of ways, including by using a book or touchscreen. We were also interested in whether children recognize the advantage of using a touchscreen to procure certain types of information, particularly variable, time-sensitive information. For example, if one wanted to learn about weather in the general sense, a book could be just as helpful as a touchscreen device. However, if one wanted to learn about *today's* weather, a touchscreen would be the more appropriate tool. To explore this, we included two learning topics for which it would be best to use a touchscreen, to assess whether children treat timely information differently. Thus our study included two types of learning topics: general and time-sensitive. Although we found no prior research on children's comprehension of time-sensitive information, we believe that because touchscreens are frequently used to learn this type of information, children may recognize this particular benefit of touchscreens. Parents were surveyed about their children's use of books and touchscreens to learn in different settings. Based on prior research (Eisen and Lillard, 2015), we predicted that children would prefer books as a learning tool for our general topics. We further expected that children would recognize that time-sensitive information is best gained from using a touchscreen device. Lastly, we predicted that children who use touchscreens frequently for educational purposes would favor the touchscreen device in our task.

MATERIALS AND METHODS

Participants

Seventy children participated, including eighteen 3-year-olds (M = 41.05 months, SD = 3.12, range = 37.1 – 45.8; 8 female), seventeen 4-year-olds (M = 55.36 months, SD = 3.51, range = 49.8 – 59.8; 7 female), eighteen 5-year-olds (M = 66.42 months, SD = 3.89, range = 60.4 –71.1; 9 female), and seventeen 6-year-olds (M = 78.72 months, SD = 4.11, range = 72 – 83.5; 9 female). Specific data on children's ethnicity was not collected but children were predominantly white and middle class, reflecting the families who volunteer for research in the community. Children were recruited from a local children's museum and from a database of families willing to bring their children to the laboratory for research. Parents provided written informed consent for their child's participation, approved by the host institution's research ethics committee. Children provided verbal assent to the experimenter before entering the testing room. Parents and children were debriefed after the study. An additional five children were tested but excluded from analysis due to inattention (3) or inability to complete the experiment (2).

Materials

The materials consisted of six books, each measuring 9 by 6.5 cm in size and 20 pages in length, as well as a black iPad mini and a white iPhone 6. Each book had a distinct cover to represent each of the six learning topics, which were: cooking, today's weather, trees, vacuum cleaners, Virginia, and yesterday's football game. Each cover displayed an image to represent the topic. For example, the cooking cover showed an image of a chef holding a plate of pasta and the Virginia cover showed an image of the state of Virginia. The touchscreen devices displayed PDF versions of these covers. To maintain consistent object positions, the books and touchscreen devices were presented to the child on a blue plastic tray measuring 45 by 30.5 cm. A female doll named "Sarah" was also presented to children for each trial.

Procedure

Participants were first introduced to Sarah the doll, which sat at the far end of the table and faced the child. The experimenter explained that Sarah wanted to learn about different topics and that she had different tools she could use to learn, but that she needed the child's help to make her choices. Underneath the table and out of sight of the participant, the experimenter placed the first book and a touchscreen device onto the tray, then lifted the tray onto the center of the table in front of the child. Whether the touchscreen device was an iPad or an iPhone was counterbalanced, as was the position of each object on the tray. For half of the participants, topics were displayed in a fixed order (trees, cooking, weather, Virginia, vacuum cleaners, and football) and for the other half of participants, the order was reversed. The six topics were chosen to cover a wide range of information that would likely be familiar to children but not so common that they would have prior experience learning about the topics using books or touchscreens. After the experimenter placed the tray with the learning tools on the table, she explained that Sarah wanted to learn about a particular topic (e.g., trees) and that Sarah had a book about that topic and an iPad (or an iPhone) with an app about that topic. A doll was chosen as "the learner" so that children would not take into account their own or the experimenter's prior knowledge about the topics. The experimenter pointed to each object as it was introduced and the order of introduction was counterbalanced. The experimenter than asked the participant to choose which tool Sarah should use to learn about the topic and explain why Sarah should use the tool. This process was repeated for all six learning topics.

Explanations of children's learning choices were coded into seven discrete categories: *preference*, in which children mention preference or desire (e.g., "She wants to"), *learning*, in which children explicitly reference learning (e.g., "I use the iPhone to learn"), *comparison*, in which children contrast the two tools (e.g., "A book has more words about it"), *action*, in which children describe a physical action that can be done with the tool (e.g., "It can scroll"), *topic-specific*, in which children directly reference the topic at hand (e.g., "It has planting"), *object-specific*, in which children directly reference an aspect of the tool ("Phones can do anything"), and *no response*, including responses of "I don't know" or "I'm not sure." A research assistant, blind to the purpose of the experiment, coded the entire dataset of explanations. A second blind research assistant coded 25% of the dataset. Interrater reliability was high (kappa = 0.88) and discrepancies were resolved through discussion with the first author.

While children were being tested, parents filled out a questionnaire about their child's use of books and touchscreens to learn at home and in school. Parents were asked whether their child primarily uses touchscreens for educational, entertainment, or other purposes. Parents were also asked about the child's personal experience or observations of others' learning about the study's specific topics from a book or a touchscreen, to account for the role of experience in children's responses. Finally, parents were questioned about their personal beliefs of the educational merits of books and touchscreens. Appendix A includes the full parent questionnaire.

RESULTS

Overall, children in our sample frequently used books, with 87.1% reading or being read to daily and the remaining 12.9% reading several times a week (see **Table 1**). Touchscreen use was more variable, with 45.7% of children using them daily, 41.4% using them weekly, and 12.9% using them less than once a week. This frequency of touchscreen use falls between the levels reported by other studies in recent years (Kabali et al., 2015; Rideout, 2013). Fisher's exact test revealed significant age differences in level of touchscreen use between 5-year-olds and all other ages, $p = 0.04$, with a much higher frequency (77.8%) of 5-year-olds shown to be daily users. No age differences were found for children's frequency of reading books, as the vast majority of children were daily readers.

TABLE 1 | Frequency of use of learning tools.

		Low (Less than once a week)	Medium (Weekly)	High (Daily)
3 years	Book	0	16.6	83.4
	Touchscreen	22.2	38.9	38.9
4 years	Book	0	5.9	94.1
	Touchscreen	17.6	53	29.4
5 years	Book	0	11.1	88.9
	Touchscreen	5.6	16.6	77.8
6 years	Book	0	17.6	82.4
	Touchscreen	5.9	58.9	35.2
Total	Book	0	12.9	87.1
	Touchscreen	12.8	41.4	45.7

Frequencies are shown as percentages. The total includes frequency of use for all ages.

Preliminary Chi-Squared analyses revealed no effects of touchscreen type (iPad or iPhone), order, or gender on children's learning choices, so these variables were collapsed in subsequent analyses. The percentages of touchscreen choices for each task at each age are shown in **Figure 1**. First, responses to each learning choice question were compared against chance performance (50%) for each age group using Binomial tests. For 3-, 4-, and 5-year-olds, learning choices did not differ from chance and children were equally likely to choose the book or the touchscreen for each learning scenario. For 6-year-olds, the touchscreen was chosen significantly more than chance for the tree question (13 out of 17, or 76%, $p = 0.049$), the weather question, (13 out of 17, or 76%, $p = 0.049$), and the vacuum question, (13 out of 17, or 76%, $p = 0.049$). For the cooking question, 6-year-olds showed some preference for the book, although not significantly more than chance (12 out of 17, or 71%). For the Virginia question and the football question, the choices of 6-year-olds did not differ from chance.

Another approach to the data, rather than look at whether a touchscreen device was used more than chance for each item, is to look at whether children at different ages distinguish among the options; that is, do they choose the touchscreen device more for one type of information than another? Because these analyses were based on categorical data, we performed non-parametric analyses for each age group across all learning choice questions. Cochran's Q test indicated that responses did not differ among the six questions for the 3-, 4-, or 5-year-olds. However, responses did differ among the six questions for 6-year-olds, $Q(5) = 13.704$, $p = 0.018$. Pairwise comparisons with McNemar's test revealed that 6-year-olds chose the book over the touchscreen significantly more for the cooking question than the tree question, $p = 0.039$, the weather question, $p = 0.008$, or the vacuum question, $p = 0.021$.

Learning choice explanations were not related to children's learning tool choices for the topic of trees, weather, Virginia, and football. For the topic of cooking, learning choice explanations were associated with tool choice, χ^2 $(6, N = 70) = 13.03$, $p = 0.043$. The association was moderately strong, Cramer's $V = 0.43$. *Post hoc* comparisons using adjusted standardized residuals show that children who chose the book were more

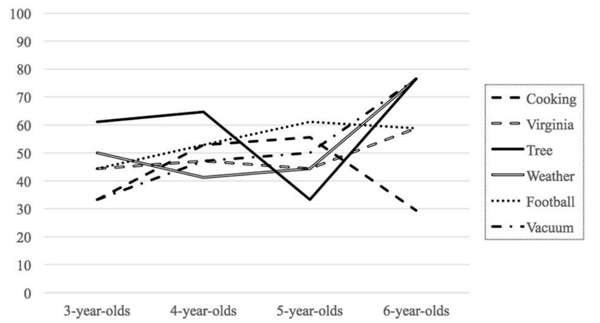

FIGURE 1 | Percentage of touchscreen choices for each topic by age group. The percentage of book choices is not shown but is the inverse of this graph.

likely to give preference explanations and children who chose the touchscreen were more likely to give object-specific explanations. For the topic of vacuum cleaners, learning choice explanations were associated with tool choice, χ^2 (6, $N = 70$) = 13.87, $p = 0.031$. The association was moderately strong, Cramer's $V = 0.45$. *Post hoc* comparisons show that children who chose the book were more likely to give action explanations and children who chose the touchscreen were more likely to give topic-specific explanations.

Interestingly, children's use of and observation of others' use of devices at home or school bore no relation to their judgments. Using Pearson's correlations, we found that children who read books less frequently (several times a week, $n = 9$) were no less likely to choose a book as a source of information than children who read books daily ($n = 61$). We also found no relation between children's tendency to choose the touchscreen in our task and their overall use of touchscreens at home or school. Children who were considered low in their touchscreen use (less than once a week, $n = 9$) were no less likely to choose a touchscreen device to get information than were children who were considered medium (weekly, $n = 29$) or high (daily, $n = 32$) users of touchscreen devices.

Parents were also asked their beliefs about the extent to which their child learns from books and touchscreens. The majority of parents (85.7%) said their child learns a lot from reading books; the other parents (14.3%) all claimed their child learns somewhat from books. Parents showed much greater variability in their assessment of learning from touchscreens. A third of parents (33.8%) claimed their child learns only a little or not at all from touchscreen devices, 45.6% claimed their child somewhat learns from touchscreens, and 20.6% claimed their child learns a lot from touchscreens. The extent to which parents stated that their child learns from books showed a trend toward being related to children's learning choice of books, $r(70) = -0.19$, $p = 0.11$, but their belief in touchscreens as a learning tool was not related to children's choice of touchscreens, $r(68) = 0.03$, $p = 0.81$. Children's primary use of touchscreens did not relate to their likelihood of choosing the touchscreen in the learning tasks or to their parent's belief about learning from touchscreens.

DISCUSSION

This study explored how children compare books, which have long been viewed as an educational tool, with the increasingly available and popular touchscreen. We hypothesized that children would show a preference for using books to learn about a variety of topics. There are several reasons for this expectation. First, when Eisen and Lillard (2015) surveyed children about the various functions of different media tools, the majority of children claimed learning as a function of books. Far fewer children said that touchscreen devices could be used for learning. Children also chose the book over other objects, including touchscreens, in a hypothetical learning scenario. Second, parents may differ in their beliefs about the potential information to be gained from either books or touchscreens. This could affect how parents discuss learning with their children and the extent to which they turn to books or touchscreens when their child wishes to learn. Books are the more conventional method of learning and past studies have shown that parents prefer to use them for educational needs (Wartella et al., 2013). Third, although touchscreen devices are increasingly integrated into some classrooms, the traditional book still reigns supreme in these settings. The consistent use of books within schools may send an implicit message of their utility in education.

Contrary to our hypothesis, we found that children did not favor books to learn in our task. Indeed, younger children showed no preference between books and touchscreens for the variety of topics about which we inquired. Only 6-year-olds showed particular preferences, and although they preferred to use a touchscreen for three of the six scenarios, they did not differ from chance in their choices for the other three. Specifically, 6-year-olds chose to use a touchscreen to learn about trees, today's weather, and vacuum cleaners. However, 6-year-olds also tended to choose the book over the touchscreen to learn about cooking, although not at a level significantly different from chance. For the two time-sensitive topics, only 6-year-olds recognized the utility of the touchscreen for up-to-date information, and they did so only for the question about today's weather. It seems rather surprising that children would think a book could provide information about yesterday's football game, but almost half of them did. Although the specific topics were meant to strike a balance between familiarity and novelty, learning about current weather may have been too common an activity and learning about football may have been too unusual, leading children to favor the touchscreen for the former but not the latter. Similarly, learning about Virginia may have been too novel or broad a concept, such that 6-year-olds were unsure which tool would be better and chose equally between them. Around the age of six, children readily produce examples of learning sources but have more difficulty describing the process of learning (Sobel and Letourneau, 2015). The 6-year-olds in our study could be too young to easily conceptualize how to learn about highly unfamiliar topics, such as football or a state. Future research might explore this topic with older children.

Children's explanations for their tool preferences illuminated only some of their choices. For the topic of cooking, children who chose the book more frequently referenced their own or the doll's preferences, as in, "I use that one too" and "She likes books better." In contrast, children who chose the touchscreen for cooking claimed object-specific reasons, such as, "It could show you a video" or "It has an app." This may reflect how adults make similar decisions about cooking. Despite the utility of touchscreens for finding recipes or displaying cooking tutorials, many people prefer a traditional cookbook. However, we found no correlation between children's tool choices and their observation of others using books or touchscreens to learn about cooking. For the topic of vacuums, children who chose the book gave explanations related to action, such as, "She can turn the pages" or "You can read it," whereas children who chose the touchscreen gave topic-specific rationales, such as, "It has a lot about vacuum cleaners" or "You can see which [vacuum] you want." It is not clear why children's explanations differed for this topic, but one possibility is that children who chose the book interpreted the question as being about manual learning, and therefore linked to physical action, whereas children who chose the touchscreen interpreted the question as "capable of learning about vacuums" in a more general sense. For all other learning topics, children's explanations were not related to their choice of tool.

Interestingly, we found no relation between children's general use of touchscreens and books and their choices in our learning task. This was unexpected, since we predicted that children who frequently used touchscreen devices would be more aware of their potential as learning tools, either through personal experience or due to parental beliefs about the educational merit of touchscreens (Cingel and Krcmar, 2013). Most parents reported regular use of books and expressed the belief that their child learned a great deal from reading or being read to. In contrast, although most parents reported their child's touchscreen use to be at least weekly, parents varied in their belief that learning takes place during these interactions, with a third of parents reporting minimal learning. As Wartella et al. (2013) determined in their survey of parental attitudes, parents are still on the fence about the instructional value of touchscreens and apps. Although parents' failure to see touchscreens as educational tools could theoretically impact their children's conceptualization of these devices as paths to learning, we found no relation between parent beliefs and children's judgments.

Danovitch and Alzahabi (2013) suggest that older children do trust technological devices as sources of information, sometimes even more than human information sources, and that adults actually prefer a technological informant. For adults, this is largely because we are aware that a touchscreen device, via its connection to the Internet, allows for unlimited information, whereas a person (or a book) is inherently finite in knowledge. Young children may lack this understanding. In fact, it is not until late in elementary school that children begin to comprehend the complexity of the Internet, and late in middle school that adolescents understand its social complexity on an adult level (Yan, 2005, 2006, 2009). Therefore, the younger children in our sample were likely unaware of the advantage the touchscreen held over the book. Yet this does not explain the choices of the 6-year-olds, who favored the touchscreen for half of the learning scenarios. Although children who were frequent touchscreen users were not more likely to choose the touchscreen in our study, they may still have a more developed understanding of the utility of touchscreen devices than their younger counterparts, perhaps due to more years of experience with touchscreens rather than greater frequency of use. Since we did not question parents about their children's past use of touchscreens, this can only be speculated.

This study had several limitations, the first of which is the restricted age range that was tested. An interesting future direction would be to examine how adults respond to these learning scenarios. It seems likely that adults will privilege the touchscreen device for learning, particularly given its integration into everyday life and the access it provides to infinite information. However, adults may also recognize that information from the Internet is often scattered, shallow, and potentially incorrect, leading them to favor books. This study was further limited by a relatively small sample size, which restricts the extrapolation of our findings. A larger sample size and an expansion of the age range to include older children and adults would enable better generalizability of the results.

Methodologically, this study differed from Eisen and Lillard (2015) in three important ways. First, in our learning scenarios children were asked to choose between two actual objects, rather than several images of objects, which we believe aided the validity of our study. Second, while children in Eisen and Lillard (2015) were asked which general object would be best for learning about a particular subject, we specified that both the book and the touchscreen (via an app) held specific information pertinent to the subject. Lastly, children were asked how a doll should make choices between each object, rather than how they themselves should make choices for their own learning objectives. Although the doll was used so that children would not take their own knowledge about the topics into account, this may have led to the different findings of each study. Perhaps children associate books with their own learning but recognize that others can learn from varied sources. The high level of book use in our sample lends support to this idea, since parents report their children learn more often from books than from touchscreen devices.

Finally, although we aimed for a broad range of learning topics for our experiment, by no means did we cover the wide variety of topics that children may use a book or touchscreen to learn about. Instead, we offered children learning scenarios that were realistic, distinctive, and could plausibly be accomplished via either tool. Future research should explore whether children's learning choices vary by domain. For example, since 6-year-olds in our study primarily chose the touchscreen to learn about trees, would they also choose the touchscreen to learn about other biological organisms? Children may favor using touchscreens or books for specific topics that were not covered by this study.

As children gain independence and agency through early childhood, they have more control over how they gather information. By examining the choices children make between different tools for learning, we can better understand optimal ways to teach them. In this study, we demonstrated that young children view books and touchscreens as equally viable methods of education. By the age of six, children show more distinct opinions about which tool is better and often judge the touchscreen as superior. As touchscreen devices are increasingly used in educational settings, we should continue to explore children's understanding of their instructive capabilities.

AUTHOR CONTRIBUTIONS

SE and AL designed the study, developed the methodology, and wrote the manuscript. SE collected the data and performed the analyses.

ACKNOWLEDGMENTS

Preparation of this article was supported by an American Montessori Society Grant to SE and AL and grants from the Brady Education and Sir John Templeton Foundations to AL. We thank the families who participated and Ashley Beamish, Meghan Ellwood, Elizabeth Gravley, Carine Leslie, and Emily Wright for their assistance.

SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: http://journal.frontiersin.org/article/10.3389/fpsyg.2016.01431

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Conflict of Interest Statement: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

frontiers in Psychology

ORIGINAL RESEARCH
published: 13 September 2016
doi: 10.3389/fpsyg.2016.01377

When Seeing Is Better than Doing: Preschoolers' Transfer of STEM Skills Using Touchscreen Games

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The purpose of this study was to examine the extent to which character familiarity and game interactivity moderate preschoolers' learning and transfer from digital games. The games were based on a popular television show and designed to test skills related to STEM (science, technology, engineering, mathematics): numerical cognition (quantity of different sets) and knowledge of a biological concept (growth). Preschoolers (3.0–5.5 years, $N = 44$) were assigned to play one game and watch a recording of an experimenter playing the other game. Learning was assessed during pre-test and post-test using screenshots from the game. Transfer was assessed using modified screenshots (near) and real-life objects (far). Familiarity was assessed by asking children to identify the television characters and program. Findings indicate that the effectiveness of the games varied by age and condition: younger children learned from the quantity game, but only when they watched (rather than played) the game. They did not transfer this information in either condition. Conversely, older children learned from the growth game regardless of whether they played or watched. However, older children only demonstrated far transfer if they watched (rather than played) the growth game. Thus, preschoolers may benefit more by watching a video than by playing a game if the game is cognitively demanding, perhaps because making decisions while playing the game increases cognitive load. Character familiarity did not predict learning, perhaps because there was little overlap between the lessons presented in the television program and game. Findings from the current study highlight the need for more research into educational games and applications designed for preschoolers in order to establish whether, how, and for whom screen media can be educationally valuable.

Keywords: STEM, digital games, touchscreens, preschoolers, transfer, learning

OPEN ACCESS

Edited by:
Gabrielle Strouse,
University of South Dakota, USA

Reviewed by:
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University of Cincinnati, USA
Ahmed Ibrahim,
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Specialty section:
This article was submitted to Developmental Psychology, a section of the journal Frontiers in Psychology

Received: *31 May 2016*
Accepted: *29 August 2016*
Published: *13 September 2016*

Citation:
Schroeder EL and Kirkorian HL (2016) When Seeing Is Better than Doing: Preschoolers' Transfer of STEM Skills Using Touchscreen Games. Front. Psychol. 7:1377. doi: 10.3389/fpsyg.2016.01377

INTRODUCTION

Young children are increasingly exposed to educational games and applications for touchscreen devices. While many developers claim that their mobile applications hold educational value, researchers know little about whether, how, and for whom these new media can promote learning. This is particularly true for digital games targeting the areas of science, technology, engineering, and mathematics (STEM). Moreover, given the cognitive demands of using interactive media, it is unclear whether young children benefit more from actively playing or watching games, especially when they are not familiar with the game or its characters. The purpose of the current study was to examine the extent to which character familiarity and game interactivity moderate preschoolers' learning and transfer from digital games.

Why Focus on STEM Skills in Early Childhood?

The USA is lagging behind other countries in science and mathematics. According to a recent international study of the proportion of young people with college degrees, the USA has dropped to 17th in science and 25th in mathematics (U.S. Department of Education, 2012). Achievement gaps in STEM-related fields appear early and persist over time. For instance, Morgan et al. (2016) examined the age of onset, over-time dynamics, and underlying mechanisms of science achievement gaps in USA elementary and middle schools. The researchers found that science achievement gaps appear before first grade and continue through eighth grade. The authors suggest early intervention is key to reducing achievement gaps in science. Similarly, number skills during the preschool years predict mathematics competency years later (Duncan et al., 2007; Locuniak and Jordan, 2008; Geary et al., 2013).

Despite the importance of early science and math skills for later academic success, STEM skills are relatively understudied in preschool populations. Nonetheless, research demonstrates that preschool-age children are capable of understanding a range of science concepts such as scientific methods (e.g., observation, hypothesis testing), physics (e.g., gravity), and biology (e.g., life cycles; see Gelman and Brenneman, 2004, for review). For instance, Rosengren et al. (1991) demonstrated that preschoolers understand growth, a basic biological concept. In this study, preschoolers were shown pictures of juvenile and adult animals and then asked to identify which pictures represented each animal as an adult. The researchers found a high performance rate, suggesting that even 3-year-olds have an understanding that in order for growth to happen, a change must ensue (e.g., the animal grows from little to big). Perceptual features, such as the relative size of different creatures, may be particularly important cues that help young children generalize biological concepts (e.g., food chains; Gluckman et al., 2014).

Similarly, young children are able to demonstrate basic mathematical skills prior to formal education (see Clements and Sarama, 2009, for review). Discriminating between number sets is one example. This skill has been demonstrated in children as young as 6 months (e.g., Xu et al., 2005). As children's math abilities grow, discriminating between sets develops into comparing and adding numerical sets without counting and resorting to guessing strategies (Barth et al., 2005). By the end of the preschool period, children are capable of comparing sets of objects based on numerosity. For instance, Barth et al. (2005) reported that 5-year old-children performed above chance (67%) when asked to compare sets of dots and identify which set was greater.

This growing body of literature indicates that young children are capable of demonstrating basic science and math skills, and that early STEM skills predict academic performance many years later. Therefore, it is vital to develop scalable, cost-effective interventions that prepare young children to be successful in science and math. We turn now to a discussion of educational media as potential tools for early intervention.

Can Young Children Learn STEM Skills from Screen Media?

Decades of research have demonstrated that educational programs can teach young children a wide range of content and skills (see Fisch, 2004, for review). Longitudinal studies suggest that educational television exposure during the preschool years predicts readiness at school entry (Wright et al., 2001) and academic achievement at least as far as high school (Anderson et al., 2001). Moreover, the effectiveness of educational television appears to be far-reaching: Mares and Pan (2013) conducted a meta-analysis of research on the effectiveness of international co-productions of *Sesame Street* and found consistently positive results for cognitive outcomes (including quantity) and learning about the world (including environment and science).

Researchers have begun to evaluate educational games and mobile applications in light of the increase in children's access to and use of interactive platforms such as tablet computers (Levine and Vaala, 2013). Some field experiments suggest that educational computer games can be effective at improving skills they are specifically designed to teach, such as pre-literacy and reading skills (e.g., Din and Calao, 2001; Segers and Verhoeven, 2005). Of particular relevance here, one previous study suggests that preschool-age children can learn math skills from digital games: Aladé et al. (2016) examined the effect of interactivity on preschoolers' ability to learn about measurement (a basic math concept) from a touchscreen game. The authors found that preschool children can indeed learn a novel measurement skill from child-directed, educational media presented on a touchscreen device. Despite the apparent efficacy of digital games for teaching a range of skills, parents appear to be particularly skeptical about the value of screen media for teaching science skills in particular (Rideout, 2014), thus the current study was designed to examine children's acquisition of both math and science skills.

Also of interest in the current study was whether children can transfer what they have learned to new problems. In order to transfer, children must develop a flexible mental representation of the educational content and recognize the connection between previously learned solutions and new problems (Fisch et al., 2005; Barr, 2013). In particular, children must recognize the deep-structure similarity (e.g., the two problems both require addition) and disregard differences in surface structure (e.g., one problem is about flowers and the other problem is about animals; Fisch et al., 2005). In the final section of this literature review, we consider factors that moderate preschoolers' direct learning and transfer from screen media.

What Conditions Lead to the Best Learning Outcomes for Educational Media?

Some young children clearly learn from some educational media some of the time. However, there is substantial variability in the effectiveness of educational media across different titles, individuals, and contexts. Here, we consider characteristics of the medium itself as well as characteristics of the viewer and testing situation that may moderate the effectiveness of educational media. While there are many factors that moderate the effectiveness of educational media, for current purposes we focus on three factors: the ease with which children can use the medium, children's familiarity with media content, and the extent to which children have to generalize in the face of perceptual differences.

Media Characteristics: The Case of Interactivity

The extent to which young children learn from screen media depends in part on the extent to which media content (Fisch, 2004, 2013) and device interfaces (Strommen, 1993) place demands on working-memory resources. Young children may be better able to navigate a simple, intuitive touchscreen interface than a game controller or computer mouse (Revelle, 2013), enabling more individualized control. If preschool-age children are able to maintain control of the game, their attention, engagement, and interest will likely increase (Calvert et al., 2005). However, the extent to which young children benefit from interactive (versus non-interactive) media is unclear.

Interactive media has been defined as when a program's output is determined by the user's input (Investopedia, 2010). As in previous research (Aladé et al., 2016; Choi and Kirkorian, 2016; Kirkorian et al., 2016), we define media as an interactive medium as one in which the child touches the screen to play a game themselves rather than watching pre-recorded video (e.g., of the experimenter playing a game). Interactive media provide contingency and feedback, encouraging a more scaffolded learning experience (Revelle, 2013; Hirsh-Pasek et al., 2015). This control allows children to go at their own pace (Hirsh-Pasek et al., 2015). Further, the feedback from interactivity is immediate and tells the player whether their choices were correct or not, allowing the player to monitor progress and connect to the game (Gee, 2005; Hirsh-Pasek et al., 2015). Thus, it may be unsurprising that older preschool-age children appear to learn specific problem-solving strategies from touchscreen games. For instance, Huber et al. (2016) assessed problem solving among 4- to 6-year-old children using the Tower-of-Hanoi task. Children played either a real-life version of the game (disks on a peg board) or a digital version of the game on a touchscreen tablet. The authors reported the same rate of learning for those who played with real objects and with the digital game (Huber et al., 2016).

Despite the potential efficacy of digital games for learning, some titles may be more effective than others. Research with digital games is limited, but research with electronic books suggests that while some interactive features draw the reader's attention to the story and produce better learning outcomes, titles with too many of these features can draw attention away from the story and hinder learning for preschoolers (see Bus et al., 2015, for review). Moreover, the specific conditions that lead to learning vary with age among younger preschoolers. For instance, 2-year-olds viewed videos on a touchscreen tablet in order to learn words (Kirkorian et al., 2016) or find hidden objects (Choi and Kirkorian, 2016). Some children interacted with an application that was specifically designed to guide attention to important information on the screen (e.g., asking children to touch the location of an object that was being labeled), while other children interacted with a more open-ended application that allowed more flexibility in how they viewed videos (e.g., letting them touch anywhere on the screen to continue). A third group of children watched non-interactive videos. Results indicated that younger (but not older) 2-year-olds learned from applications that guided attention, but not from applications that were more flexible or from non-interactive video. Similarly, Aladé et al. (2016) reported that children between 3 and 5 years of age were better able to transfer a measurement strategy from screen media to perceptually different stimuli when they watched a digital game than when they actively played the game. Thus, the potential benefits of interactive media may only be realized when the cognitive demands of playing the game do not exceed the child's ability to both play the game and process the content.

Individual Characteristics: The Case of Familiarity

Fisch (2013) theorized that certain viewer characteristics, including prior knowledge and high working-memory capacity, help children learn from educational media. One characteristic, character familiarity, is of interest for the current study. Being familiar with a character includes identifying a character by name (Calvert, 2002; Lauricella et al., 2011). According to Fisch's (2013) model, if a viewer is familiar with a character, they do not have to use working-memory resources to learn about the character and instead can focus on the content to be learned. Lauricella et al. (2011) tested this with 21-month-old toddlers using a seriation task. Toddlers watched either a familiar or unfamiliar puppet place cups in order from smallest to biggest and then nest smaller cups inside larger ones. Children were then given an opportunity to play with the real cups, and researchers scored their imitation based on nesting smaller cups inside of larger ones. Only those who watched the familiar puppet outperformed those in a baseline condition who did not see either video. Others have reported similar findings (e.g., Howard Gola et al., 2013).

Familiarity can also include experience with a particular title. If children are familiar with a particular program, they understand the format of the show (e.g., prompts inviting the audience to respond to questions), which may further support comprehension (Crawley et al., 2002). In support of this hypothesis, Piotrowski (2014) reported that children 3–5 years of age learned more from *Dora the Explorer* (a preschool show) when they were familiar with the program. In particular, the children who were familiar with the show benefited from invitations to respond to the character's questions. While familiarity with an "interactive" television show appears to moderate learning, research has yet to establish the extent to which familiarity moderates children's learning from truly interactive media, such as digital games.

Transfer Demands: The Case of Perceptual Similarity

With the aid of familiarity, preschool-age children are capable of transferring information from educational media to a variety of problems. However, children may have particular difficulty when they have to generalize to problems that are perceptually different from those depicted in screen media (Fisch et al., 2005;

Barr, 2013). For instance, Crawley et al. (1999) reported that 3- to 5-year-old children were able to generalize a problem-solving strategy from *Blue's Clues* (a preschool program) after just one viewing when the test problem was similar to those seen in the show; however, they were only able to transfer to problems with different surface features when they viewed the same episode five times. Similarly, Aladé et al. (2016) found that preschoolers generalized a measurement strategy after either watching or playing a digital game when pictures in the test stimuli resembled those seen in the game (e.g., other animals); however, the children only generalized this strategy to less similar pictures (e.g., robot) when they watched (rather than played) the game. Thus, transfer in the face of perceptual dissimilarity appears to be a difficult task that may be hindered by more cognitively demanding media experiences.

Overview of the Current Study

Screen media have the potential to teach STEM skills to young children. However, the exact conditions that produce the best learning outcomes appear to vary by viewer characteristics, such as age and familiarity with the characters and program. While some children benefit from interactive media, others may benefit equally (or more) from viewing non-interactive demonstrations, especially when transferring to perceptually different problems. Research that directly assesses the extent to which young children can learn and transfer STEM-related skills from digital media is lacking. It is imperative that researchers identify whether, how, and for whom screen media may be educational in order to inform caregivers, educators, and practitioners about effective learning experiences for young children.

The current study was designed to examine the extent to which familiarity and interactivity affect preschoolers' learning from STEM games. Preschoolers (3–5 years) played one STEM game and watched a recording of an experimenter playing another STEM game. The experimenter assessed prior skill knowledge before children experienced each game. Direct learning and transfer were assessed after each game. In addition, the researcher assessed each child's familiarity (with the characters and program) and receptive vocabulary.

In line with Fisch's (2013) capacity model, we predicted that prior knowledge related to the educational content (i.e., pre-test scores) and familiarity with the characters and program featured in the game (i.e., ability to identify and name characters and television program) would reduce cognitive load during the games and therefore lead to greater direct learning and transfer. Given that prior research has mixed results regarding interactivity (Aladé et al., 2016; Choi and Kirkorian, 2016; Kirkorian et al., 2016), the effect of playing games compared to watching game-play was an open research question. If playing games supports learning (e.g., increasing engagement, scaffolding learning, allowing children to learn at their own pace), then we expected direct learning and transfer to be higher when children played (rather than watched) the game. On the other hand, if playing games disrupts learning (e.g., increasing cognitive load), then we expected children to learn more from the game they watched (rather than played).

MATERIALS AND METHODS

Participants and Design

The study was carried out in accordance with the recommendations of the University of Wisconsin-Madison Education and Social/Behavioral Science Institutional Review Board with written informed consent from all participants' guardians. Participants were 44 preschoolers (27 males) between 3 and 5.5 years of age ($M = 4.2$ years, $SD = 0.8$ years) recruited through local preschools and mailing lists. As described in Section "Results," preliminary analyses indicated that the impact of the games varied by age. Thus, for the purpose of analysis, the sample was divided into younger ($n = 22$, $M = 3.56$ years, range = 3.04–4.29 years) and older groups ($n = 22$, $M = 4.86$ years, range = 4.39–5.41 years).

Of the 27 parents (61% of sample) who responded to the parent survey, 17 (63%) identified their child as White/Caucasian (non-Hispanic), four (15%) as Asian/Pacific Islander, one (0.4%) as Black/African American, and one (0.4%) as Hispanic; the remaining four (15%) identified their child as other/mixed race. Parent education averaged 19.07 years ($SD = 2.44$, range: 14–24). Data were collected from October 2014 to April 2015.

Children were randomly assigned to groups within a 2(condition: play versus watch) × 2(game: growth versus quantity) × 2(order: play first versus watch first) mixed design, with condition and game as repeated measures. Half of the children played the growth game and watched the quantity game ($n = 22$, $M = 4.15$ years), while the remaining children played the quantity game and watched the growth game ($n = 22$, $M = 4.27$ years). The order of conditions was counterbalanced with the constraint that about half of the children were randomly assigned to play first, while the other half watched first.

The children were also randomly assigned to one of two question sets that were identical in structure but varied in specific content (e.g., asked to identify which of three sets of items contained "3" versus "5", asked to sort pictures of chickens versus penguins in order of increasing age). Preliminary analyses indicated that performance did not differ by question set, so analyses collapsed across this variable.

Parent Survey

Parents were asked to complete an online survey including demographic information, media use, and child's familiarity with the children's television show on which the games were based (*Dinosaur Train*). In order to estimate overall media use, parents reported the number of minutes that their child used different types of media on the previous day. Categories included viewing non-interactive video content (television program, DVD) on a television, computer, streaming device, or mobile device; playing a game on a computer, video-game console, handheld gaming device, or mobile touchscreen device; and using a digital reading device (Nook, LeapFrog). In order to assess children's familiarity with *Dinosaur Train,* parents were asked how familiar their child was with the show (very, a little, not at all) and how often their child watched the show (4–5 days per week, 1–2 days per week, 1–2 days per month, never/almost never).

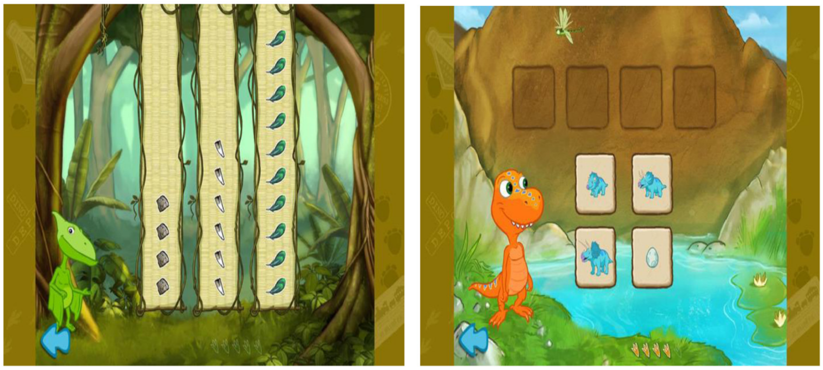

FIGURE 1 | Screenshot of the quantity game (*Don's Collections,* Left) and growth game (*Life Cycles,* Right).

Stimuli and Apparatus

The touchscreen device used in this study was a *Samsung* Galaxy Tab 10.1. The children played and viewed professionally produced games based on the show *Dinosaur Train*. *Dinosaur Train* is a Public Broadcasting Station (PBS) television program that targets basic scientific thinking skills with a goal to teach about natural history, paleontology, and life sciences (PBS Kids, 2014). For this study, we used a low-cost mobile application based on *Dinosaur Train* entitled *Mesozoic Math Adventures*, targeting science and math skills in children 3–6 years of age (PBS Kids, 2014). The two games used in this study emphasized numerical cognition (e.g., quantity, set size) and the biological concept of growth (e.g., plants and animals get larger as they grow older). Screenshots from each game are depicted in **Figure 1**.

The quantity game, *Don's Collections,* is designed to test children's knowledge of collections, organization and presentation of data in a bar chart, and ability to compare different quantities of data (PBS Kids, 2014). Throughout the game, the character Don asks numerical comparison questions, such as: "Which one do I have the most of? Which one do I have the least of? Which one has more than this one? Which one do I have 5 of?" Children responded by touching the corresponding column. If the answer was incorrect, Don told the player that the answer was incorrect and suggested to try again. He then repeated the question and waited for the response. If the answer was correct, the game advanced to the next question. There were five collections with three questions each for a total of 15 questions.

The growth game, *Life Cycles,* is designed to test knowledge of life cycles and growth by putting organisms in order from youngest to oldest (PBS Kids, 2014). The growth game began with Buddy introducing his hypothesis ("Maybe little things grow into big things!"). The player was asked to put four tiles in order from youngest to oldest. Children moved the tiles to the spaces above by touching and dragging them to the corresponding location in the sequence. If a player moved a tile to an incorrect location, a red "X" appeared in the location and the tile automatically returned to its starting position. If the player was correct, a bell sound was played, signifying that the location was correct, and the tile locked into place. In other words, when a player was correct, they were no longer able to choose from the correct tiles, thus removing them as possible choices. In total, there were five trials with four tiles to complete on each trial.

Children were randomly assigned to play one of the games (as described above) and watch the other. In the watch condition, children viewed a video of an experimenter playing the game. In this condition, children could see a full-screen view of the game (as in the play condition) and the experimenter's hand as she touched the screen to play the game (**Figure 2**). Thus in the watch condition, children only viewed correct game responses, and they could not control the pace of the game or alter its outcome.

Procedure

Children were tested individually in an empty room at their preschool or in a laboratory on the university campus. **Figure 3** visually depicts the procedure, which lasted approximately 30 min. Each assessment is described in detail in the following sections. In brief, the general procedure was as follows: first, the child completed the familiarity assessment. Afterward, the child completed assessments for the first game (either watch or play, depending on the assigned condition). The order of the assessments for each game was: (1) pre-test to assess prior knowledge, (2) either play or watch the game, (3) post-test for direct learning, (4) post-test for near transfer, and (5) post-test for far transfer. After completing all post-test assessments for the first game, the child completed the assessments for the second game in the alternate condition (play or watch). After completing both games and learning assessments, the child completed a receptive vocabulary test.

Assessments

Familiarity

In order to test their familiarity with the characters, the participants were shown a picture of the characters found in the games (Don and Buddy). The children were asked two questions of each character: (1)"Do you know who this character is?" and (2) "What is their name?" A final question asked whether they knew what program the characters were from, giving a total of five questions asked. The familiarity score was the sum of all questions answered correctly or in the affirmative (range: 0–5).

FIGURE 2 | Child watching a recording of an experimenter playing the growth game.

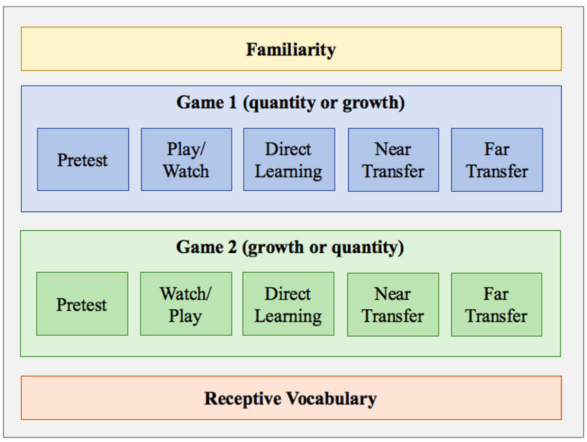

FIGURE 3 | Visual depiction of procedure; tasks were presented in order from top to bottom and left to right.

Prior Knowledge and Direct Learning

The purpose of this assessment was to determine whether children learned math and science skills from the games and could use that knowledge in the same context. This assessment was used at pre-test to assess prior knowledge and at post-test to assess direct learning. The format of the questions was the same during pre-test and post-test (e.g., asking which collection contained an exact number), but the specific content varied from one assessment to the next (e.g., asking which set contained 3 versus 5).

The experimenter showed the child screenshots taken directly from the games and asked questions using the same script as the hosts of each game. The only differences between this assessment and the game itself were that the children viewed printed screen shots for the assessments (rather than viewing on the touch screen) and responded to questions from the experimenter (rather than from the on-screen character). For example, in the quantity game, the child might be shown a printed version of the screenshot shown in **Figure 1** (left), and then be asked questions similar to those found in the game, such as "What does Don have the most of?," "What does Don have 3 of?" Children were asked two questions for each of three screen shots, for a total of six questions at pre-test and another six questions at post-test.

Similarly, in the growth game, children were shown a printout of a screenshot such as that in **Figure 1** (right), with cutouts of the four pictures in the same location as they appeared in the game. Children were then asked to slide the cutouts onto the squares so that they appeared in order from youngest to oldest. Children were shown two screen shots at pre-test and another two screenshots at post-test.

Near Transfer

To succeed on the near transfer task, children were required to transfer what they learned in the game to a novel-but-similar scenario. The near-transfer task was identical to the direct-learning task except that images of contemporary objects and animals (e.g., trucks, chickens) replaced the thematically relevant ones that were found in the games (e.g., rocks, dinosaurs). These images were superimposed on the backgrounds used in the direct-learning test. For example, in the growth game, one item used is the lifecycle of a triceratops. In the near transfer task, the child was shown the lifecycle of a penguin. Both animals hatch from eggs, produce young that resemble the adult, and end with a larger adult animal. The questions were analogous to those asked in the direct-learning assessment. See **Figure 4** for examples of the near-transfer stimuli for the quantity and growth games.

Far Transfer

To succeed on the far transfer task, children were required to transfer what they learned in the game to a scenario that was unrelated to *Dinosaur Train* using three-dimensional

FIGURE 4 | Examples of images used in the near-transfer assessment for the quantity game (Left) and growth game (Right).

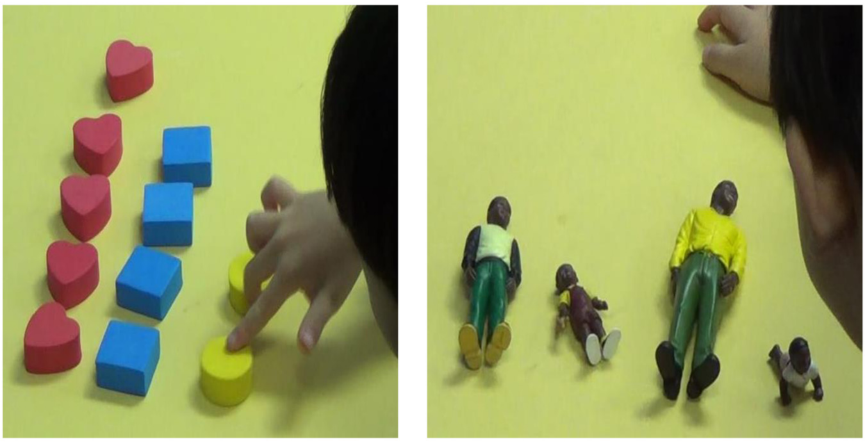

FIGURE 5 | Examples of stimuli used in the far-transfer assessment for the quantity game (Left) and growth game (Right).

objects. Thus, the surface features of the far-transfer tasks differed substantially from the games: following the quantity game, children were asked questions about sets of foam blocks; following the growth game, children were asked to put dolls (infant, young child, older child, adult) in order from youngest to oldest (**Figure 5**). Despite the differences in surface features, the questions asked during the far-transfer tasks were analogous to those used for direct learning and near transfer.

Receptive Vocabulary

Receptive vocabulary was assessed using the Receptive One-Word Picture Vocabulary Test – Fourth Edition (ROWPVT-4). The ROWPVT – 4 is an individually administered, norm-referenced assessment of an individual's ability to match a spoken word with a picture of its referent (Brownell and Martin, 2011). The distribution of standard scores has a mean of 100 and standard deviation of 15. Children viewed full-color pictures of four objects and were asked to point to the picture that matched a word (e.g., "Flower. Which one is flower?"). Children were asked increasingly difficult words until they answered six out of eight incorrectly. A standardized score was determined using norms based on the child's age and sex. The distribution of standard scores has a mean of 100 and standard deviation of 15.

Coding

Learning and Transfer

During each session, the experimenter noted the child's responses to questions for pre-test and post-test assessments. For the quantity game, the experimenter recorded whether children selected the correct column (out of three) in response to each question. The dependent variable was the proportion of questions answered correctly during the pre-test and each of the three post-tests (direct learning, near transfer, far transfer). For the growth game, the experimenter initially recorded the order in which children placed the tiles or objects when asked to sort from youngest to oldest. The dependent variable was the proportion of tiles or objects that were placed in the correct location during the pre-test and each of the three post-tests.

Errors during Game Play

We recorded videos of experimental sessions for approximately 55% of the sample. For these children, videos were subsequently coded for the number of errors that children made while playing either the quantity game ($n = 12$) or the growth game ($n = 12$). For instance, in the quantity game, an error was scored if children selected an incorrect column (e.g., the column with the greatest number objects when asked for the column with the least number of objects); in the growth game, an error was scored if children dragged a tile to an incorrect location (e.g., tried to place the picture of the oldest animal in the spot for the youngest animal). The dependent variable was the proportion of all possible errors that were committed by children. For both games, the total possible errors across all questions equaled 30.

RESULTS

Descriptive Statistics

Children's mean vocabulary score was 111 ($SD = 12$, range = 83–137). When asked how much time their child spent using screen media on the previous day, parents reported an average of 33 min watching television ($SD = 55$, range = 0–240) and 6 min playing games on a touchscreen device ($SD = 11$, range = 0–30). When asked how familiar their child was with the program *Dinosaur Train*, parents reported "not at all" (23%), "a little" (38.5%), and "very" (38.5). When asked how often their child watched the program, parents reported "never or almost never" (38.5%), "infrequently (about 1–2 days per month)" (27%), and "some (about 1–2 days per week)" (34.5%). None of the individual difference measures (e.g., vocabulary, parent education, media use) were associated with any of the outcome measures of interest, so they are not considered further.

Correlations between Familiarity, Prior Knowledge, and Learning

We hypothesized that children's familiarity with the characters and program would predict direct learning and transfer from the games. Familiarity as measured in the lab (based on children's recognition of and ability to name the characters and program featured in the game) was marginally correlated with parent-reported familiarity with the show ($r = 0.35$, $p = 0.091$) and frequency viewing the show ($r = 0.35$, $p = 0.084$). However, familiarity with the characters and show was not correlated with performance on any of the learning assessments for either game. **Table 1** depicts correlations between scores on the pre-test and three post-tests in the watch condition (above the diagonal) and play condition (below the diagonal).

TABLE 1 | Partial correlations (controlling for age) between familiarity and learning assessments.

	1	2	3	4	5
(1) Familiarity	–	0.04	−0.25	0.01	0.04
(2) Pre-test	0.05	–	0.47**	0.35*	0.39*
(3) Direct learning	0.08	0.12	–	0.44**	0.51***
(4) Near transfer	0.03	0.21	0.70***	–	0.24
(5) Far transfer	−0.07	0.09	0.34*	0.51***	–

*Familiarity was based on recognition and identification of the characters and television program. Learning assessments included the proportion of questions answered correctly during pre-test (prior knowledge), direct learning, near transfer, and far transfer. Numbers above the diagonal are for the watch condition, while those below the diagonal are for the play condition. df = 41. *p < 0.05, **p < 0.01, ***p < 0.001.*

We further hypothesized that prior knowledge (measured at pre-test) would be associated with greater learning and transfer (measured at post-test). As can be seen in **Table 1**, pre-test scores were significantly correlated with post-tests in the watch condition only. In the play condition, pre-test scores were not associated with direct learning or transfer. However, direct learning from the game was associated with near and far transfer in both conditions.

Learning from Watching versus Playing Games

Of particular interest in the current study was the impact of interactivity on learning and transfer. The omnibus analysis was a 2(age group: younger, older) × 2(game played: quantity, growth) × 2(condition: watch, play) × 4(test: pre-test, direct learning, near transfer, far transfer) mixed analysis of variance (ANOVA) with condition and test as repeated measures. The dependent variable was the proportion of questions answered correctly on each of the four tests. This analysis revealed several significant interactions, including a four-way interaction between all factors, $F(3,120) = 5.55$, $p = 0.001$, $?^2 = 0.12$. Visual inspection of the data revealed that the pattern of results differed for younger and older children and for each game. In order to capitalize on the within-subjects design of the study, and to address key hypotheses regarding direct learning and transfer (compared to prior knowledge assessed at pre-test), subordinate analyses entailed paired-samples *t*-test comparing each post-test assessment to pre-test for younger versus older children, for each game, and for each condition. The pattern of results was different for each game, so they are discussed separately.

Quantity Game

Quantity scores are plotted as a function of age and condition in **Figure 6**. It seems that the quantity game was too simple for the older children. Pre-test scores were already over 75%, thus post-test scores were (unsurprisingly) not significantly different from pre-test scores (all ps > 0.250).

Younger children were able to learn from the quantity game, but only when watching the game (not when playing it). Younger preschoolers who watched this game had higher scores on the direct post-test assessment than on pre-test, $t(12) = 3.21$, $p = 0.008$, $d = 0.90$. However, those who played this game did not do better on the direct assessment than on pre test, $p > 0.250$, $d = 0.08$. Even though younger children were able to learn from this game (in the watch condition only), this learning did not generalize to near and far transfer (ps > 0.250).

Growth Game

Growth scores are plotted as a function of age and condition in **Figure 7**. Whereas, the quantity game appeared to be too simple for older children, the growth game appeared to be too difficult for younger children. There was evidence of a floor effect for this

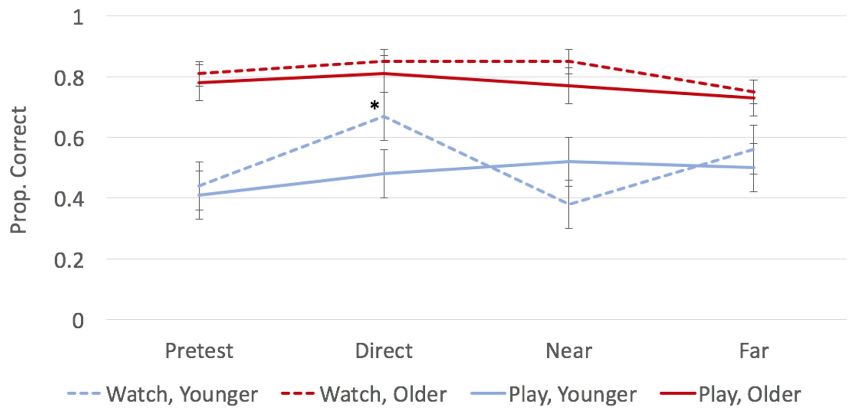

FIGURE 6 | Average proportion of quantity questions answered correctly during each test as a function of age and condition. Bars represent ± one standard error. Points marked with an asterisk (*) indicate significant difference from pre-test at $p < 0.05$.

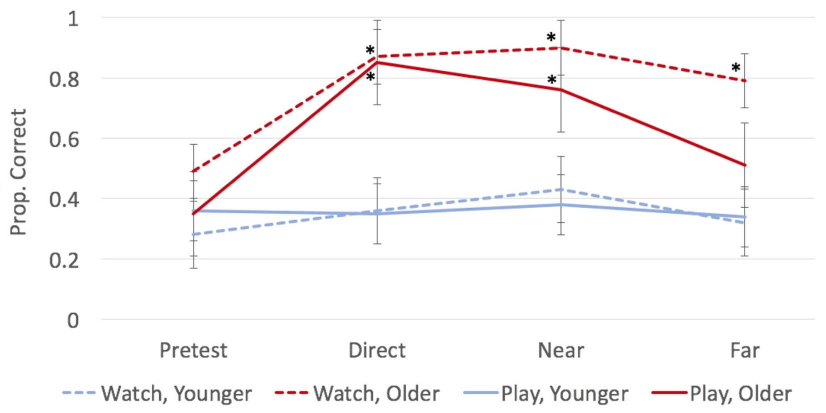

FIGURE 7 | Average proportion of growth questions answered correctly during each test as a function of age and condition. Bars represent ± one standard error. Points marked with an asterisk (*) indicate significant difference from pre-test at $p < 0.05$.

game, insofar as no post-test scores exceeded the relatively low pre test scores for younger children (all $ps > 0.10$).

Older children, on the other hand, did seem able to learn from the growth game. Direct learning scores were significantly greater than pre test scores in both the watch and play conditions, $t(12) = 3.67$, $p = 0.003$, $d = 1.07$, and $t(8) = 3.24$, $p = 0.012$, $d = 1.15$, respectively. Moreover, this learning generalized to the near-transfer test, which exceeded pre test in both the watch and play conditions, $t(12) = 3.73$, $p = 0.003$, $d = 1.19$, and $t(8) = 2.34$, $p = 0.047$, $d = 0.79$, respectively. However, learning in the growth game generalized to the far-transfer test only in the watch condition, $t(12) = 2.36$, $p = 0.036$, $d = 0.66$. The older children did not do better on far transfer than on pre test when they played (rather than watched) this game ($p > 0.250$, $d < 0.25$).

Correlations between Game Errors and Subsequent Learning

Although children saw an errorless execution of the game in the watch condition, they were free to make errors in the play condition. We scored the number of errors made by children when playing one of the two games. Of particular interest was the extent to which the number of errors during the game was associated with tests of direct learning and transfer after the game. We calculated partial correlations between frequency of errors and post-test scores, controlling for age and pre test score. The number of game errors was negatively correlated with post-test measures of direct learning and near transfer, $r(20) = -0.56$, $p = 0.007$, and $r(20) = -0.70$, $p < 0.001$, respectively. In other words, children who made fewer errors while playing the game also performed better on tests of direct learning and near transfer, regardless of age and prior knowledge at pretest. However, the correlation between game errors and far transfer was not significant ($p > 0.250$).

DISCUSSION

Decades of research has demonstrated that preschool-aged children can learn a wide range of knowledge and skills from educational media (Fisch, 2004; Anderson and Kirkorian, 2015). However, research on interactive media has not kept pace with young children's access to and use of digital games and mobile applications that purport educational value. Given the importance of early STEM skills for later academic success, it is crucial that researchers establish whether, how, and for whom educational media may foster early learning in these domains. The current project was designed to examine the impact of interactivity on young children's direct learning and transfer from games that emphasize math and science skills, and the extent to which child characteristics (familiarity, prior knowledge) are associated with learning from these games.

Associations between Familiarity, Prior Knowledge, and Learning

We predicted that familiarity would reduce cognitive load, and therefore be correlated with greater learning and transfer from the game. Contrary to this prediction, we found character familiarity was not correlated with any learning outcomes. In previous research, familiarity with both characters (Lauricella et al., 2011) and programs (Piotrowski, 2014) has been found to increase toddlers' learning from video. However, the relation between familiarity and learning is not straightforward. For instance, Kirkorian et al. (2012) found that toddlers were not more likely to imitate a familiar (versus unfamiliar) character, despite attending more to the demonstration performed by a familiar character (as measured by eye movements). Thus, character familiarity does not always lead to increased learning.

In the current study, we tested children's familiarity with characters from a popular television show (*Dinosaur Train*). However, we assessed learning from games based on the show, rather than the show itself. The game emphasized lessons that are not central to the television show (e.g., numerical cognition), and the format was substantially different from that in the television show (e.g., characters in the game spoke directly to the audience, asked questions, and provided feedback). Thus there may be limits to the benefit of character familiarity, depending on similarities between different learning contexts (e.g., show versus game).

We also hypothesized that prior knowledge (i.e., pre-test scores) would lead to greater direct learning and transfer. Interestingly this hypothesis was supported only when children watched a game; prior knowledge was not associated with learning when children played a game. The reason for this difference is unclear. Perhaps the act of playing the game drew more attention to the game mechanics rather than the educational lesson. As a result, children may have invested more effort in remembering the gestures required to interact with the game (e.g., tap in the quantity game versus slide in the growth game) than remembering their prior conceptual knowledge that would help them to answer questions correctly.

Impact of Interactivity on Direct Learning and Transfer

Prior research demonstrates that young children have difficulty transferring information from video, particularly when test problems differ substantially from examples provided in the video (i.e., far transfer; Crawley et al., 1999). Research has been mixed regarding whether interactivity during a game would enhance or impede subsequent learning from that game. While interactivity may support learning, the specific conditions that lead to the best learning outcomes appear to vary with age, at least among younger preschoolers (Choi and Kirkorian, 2016; Kirkorian et al., 2016). Moreover, Aladé et al. (2016) found that playing a digital game (as opposed to watching a recording of that game) may be particularly detrimental to transfer. Specifically, they found that 3- to 5-year-old children applied a measurement strategy to images that resembled those presented in a game, regardless of whether they played the game themselves or watched a recording of the game. However, they only applied the measurement strategy to images that differed from those presented in the game when they watched a recording of the game.

Findings from the current study replicate those of Aladé et al. (2016) using games that purport to teach skills related to numerical cognition (e.g., number, set size comparison) and biological concepts (e.g., growth, life cycles). Moreover, our findings extend prior research by demonstrating a developmental progression in the extent to which children learn and transfer from interactive and non-interactive experiences. Younger children were able to learn from one of the games, but only when they watched a recording of the game; children who actively played the game themselves did not demonstrate pretest–posttest gains. Moreover, learning in the watch condition did not extend to transfer, even when using backgrounds that were identical to those in the game (near transfer). Thus, younger preschoolers had difficulty generalizing information beyond the digital game, and they only did so when cognitive load was relatively low (i.e., direct learning in the watch-only condition).

Older children, on the other hand, demonstrated both direct learning and near transfer from one of the games, regardless of whether they played or watched that game. However, learning only generalized to far transfer with three-dimensional objects when children watched a recording of the game; performance on the far transfer task did not exceed performance at pre-test when children played the game themselves. As in the study by Aladé et al. (2016), it seems that interacting with the game prevented children in the current study from transferring to perceptually different problems.

Together our findings suggest that children may learn equally well when watching or playing a game when the task is well within the child's abilities (e.g., direct learning among older preschoolers). However, watching a game may be more beneficial than playing a game when the task is at the upper limits of the child's abilities (e.g., direct learning among younger children, far transfer among older children).

Any generalization of information from educational media to real-life scenarios requires that children form flexible representations that can be readily applied in a variety of contexts (Fisch et al., 2005; Barr, 2013). Perhaps the additional cognitive burden of interacting with a game prevents children from extracting the deep structure of problems, and instead leads them to "over-encode" the surface features (e.g., particular images in the games, gestures required to play the game). Indeed, this interpretation is consistent with Aladé et al.'s (2016) finding that preschoolers who played a game outperformed those who watched a recording of the game when the test involved images that were perceptually similar to those presented in the game. Thus, interactive features may support direct learning at the expense of transfer to perceptually dissimilar scenarios.

Implications and Future Directions

Current findings suggest that young children can learn from digital games, but that transfer from these games may be particularly difficult. Children may benefit most from non-interactive media when task demands are high. However, it is important to note that these findings are based on a convenience sample of mostly White/Caucasian and highly educated families. Further research is needed to determine generalizability of these findings. Achievement gaps in math and science appear early and persist over time, thus it is critical for future research to explore the efficacy of both interactive and non-interactive educational media among a socioeconomically diverse sample of children.

Further, it is important to emphasize that children in this study watched a flawless execution of one game but were free to make errors when playing the other game. Although some research suggests that incorrect examples help school-age children learn (Durkin and Rittle-Johnson, 2012; Booth et al., 2013), other research suggests that this practice only benefits advanced school-age students (Heemsoth and Heinze, 2014). Those students with relatively low prior knowledge, who may be considered more similar to preschool-age children, learned more from correct examples (Heemsoth and Heinze, 2014). Therefore, children in the current study may have learned less from playing (versus watching) games because they had conflicting memory of correct and incorrect responses to questions. This interpretation is supported by our own finding that children who made more errors when playing a game had lower scores on tests of direct learning and near transfer. However, the frequency of errors did not predict performance on far transfer assessments, perhaps because far-transfer scores were generally lower (and therefore less variable) than those for direct learning or near transfer. A follow-up study can more directly evaluate the hypothesis that correct examples support learning by comparing children in the current conditions to those who view a recording of an experimenter making errors while playing the game. Additionally, it may be that children take longer to master a concept when playing a game (particularly if they make many errors), but eventually develop greater mastery. Thus, future research should evaluate learning and transfer after repeated exposure to games, providing more time for children to learn and practice skills.

Finally, the current findings are limited to just one type of game. It is noteworthy that the games used in the current study did not start with a lesson to teach children about an underlying math or science skill. Thus children were only able to learn through trial and error, and the feedback provided by the characters in the game only indicated whether responses were correct or incorrect, rather than scaffolding children by explaining why answers were incorrect (Hirsh-Pasek et al., 2015). This would explain why playing the game in the current study did not lead to robust learning and transfer. Future research should examine particular features of digital games that lead to robust learning and flexible representations.

CONCLUSION

Young children are using digital games at increasing rates, and many titles are advertised as educationally valuable. However, current findings demonstrate that learning and transfer cannot be assumed. The extent to which young children learn from screen media depends on a wide range of individual characteristics and media features, and young children may have particular difficulty generalizing information to new scenarios. Thus, it is critical to identify whether, how, and for whom educational media can be effective in order to maximize educational impact.

AUTHOR CONTRIBUTIONS

ES gathered information for the literature review, conducted the study, conducted analysis on the data, and wrote the manuscript as a part of her Master's Thesis at University of Wisconsin – Madison. For publication purposes, ES worked on editing to fit the format of Frontiers. HK contributed to this manuscript by assisting with coding, data analysis, and editing as ES' mentor at University of Wisconsin – Madison and co-author of this study.

ACKNOWLEDGMENTS

ES is now at the Colorado Department of Education. We wish to thank Koeun Choi, Roxanne Etta, Mary Matoba, and Hailey Deluca for their assistance with data collection.

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Conflict of Interest Statement: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

frontiers in Psychology

ORIGINAL RESEARCH
published: 12 September 2016
doi: 10.3389/fpsyg.2016.01308

Is Handwriting Performance Affected by the Writing Surface? Comparing Preschoolers', Second Graders', and Adults' Writing Performance on a Tablet vs. Paper

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OPEN ACCESS

Edited by:
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University of South Dakota, USA

Reviewed by:
Sabine Heim,
Rutgers, The State University of New Jersey, USA
Frank Domahs,
University of Marburg, Germany
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Specialty section:
This article was submitted to Developmental Psychology, a section of the journal Frontiers in Psychology

Received: *26 May 2016*
Accepted: *16 August 2016*
Published: *12 September 2016*

Citation:
Gerth S, Klassert A, Dolk T, Fliesser M, Fischer MH, Nottbusch G and Festman J (2016) Is Handwriting Performance Affected by the Writing Surface? Comparing Preschoolers', Second Graders', and Adults' Writing Performance on a Tablet vs. Paper. Front. Psychol. 7:1308. doi: 10.3389/fpsyg.2016.01308

Due to their multifunctionality, tablets offer tremendous advantages for research on handwriting dynamics or for interactive use of learning apps in schools. Further, the widespread use of tablet computers has had a great impact on handwriting in the current generation. But, is it advisable to teach how to write and to assess handwriting in pre- and primary schoolchildren on tablets rather than on paper? Since handwriting is not automatized before the age of 10 years, children's handwriting movements require graphomotor and visual feedback as well as permanent control of movement execution during handwriting. Modifications in writing conditions, for instance the smoother writing surface of a tablet, might influence handwriting performance in general and in particular those of non-automatized beginning writers. In order to investigate how handwriting performance is affected by a difference in friction of the writing surface, we recruited three groups with varying levels of handwriting automaticity: 25 preschoolers, 27 second graders, and 25 adults. We administered three tasks measuring graphomotor abilities, visuomotor abilities, and handwriting performance (only second graders and adults). We evaluated two aspects of handwriting performance: the *handwriting quality* with a visual score and the *handwriting dynamics* using online handwriting measures [e.g., writing duration, writing velocity, strokes and number of inversions in velocity (NIV)]. In particular, NIVs which describe the number of velocity peaks during handwriting are directly related to the level of handwriting automaticity. In general, we found differences between writing on paper compared to the tablet. These differences were partly task-dependent. The comparison between tablet and paper revealed a faster writing velocity for all groups and all tasks on the tablet which indicates that all participants—even the experienced writers—were influenced by the lower friction of the tablet surface. Our results for the group-comparison show advancing levels in handwriting automaticity from preschoolers to second graders to adults, which confirms that our method depicts handwriting performance in groups with varying degrees of handwriting automaticity. We conclude that the smoother tablet surface requires additional control of handwriting movements and therefore might present an additional challenge for learners of handwriting.

Keywords: handwriting, movement kinematics, writing acquisition, children, graphomotor control, tablet

INTRODUCTION

The rapid technological developments and advanced digitization in all aspects of human life require research to assess the significance of how to impart knowledge to students via these new media. When students enter school today they are already members of the generation known as *digital natives* (Chicu et al., 2014). They understand how to use computers to quickly find and assimilate new information. The teacher's challenge is to use the technology and help students in mastering new subjects in a creative, autonomous, critical, and communicative way. Nevertheless, new technologies such as tablets are currently only selectively used in schools (at least in Germany) as revealed by the International Computer and Information Literacy Study in 2013 (Bos et al., 2014). The results of the ICILS show that only 6.5% of eighth graders in Germany attend a school that uses tablets for teaching purposes (EU average: 15.9%; Australia: 63.6%). Should the answer to this low percentage be to blindly introduce tablets to schools? Or is there a need to assess specific advantages and disadvantages of tablet use before their introduction? In support of the latter, the purpose of our study was to investigate whether it makes a difference for beginning learners (preschoolers and second graders) to write on a tablet screen compared to on common paper. Further, we compared these results to those of experienced writers (adults) to explore how the use of tablets influences groups with different levels of handwriting abilities.

Handwriting requires the coordination of a complex and fine-tuned mechanism involving multiple muscles in the hands, arms, and even the shoulder (Latash, 1993; Huber and Headrick, 1999). Their precise interplay generates skilled and controlled movements with a writing instrument (e.g., a pen or a pencil). Writing involves the execution and combination of specific strokes in a particular sequence. Furthermore, to produce fluent writing movements one must constantly use visual monitoring and sensorimotor feedback (Fischer and Wendler, 1994; Tseng and Chow, 2000). Handwriting models are typically organized hierarchically (Flower and Hayes, 1981; Van Galen, 1991; Berninger et al., 1998). These models postulate that activities at lower levels (e.g., graphomotor planning and execution) interact with performance at higher levels (e.g., syntax, semantics, creation of ideas; Van Galen, 1991; Abbott and Berninger, 1993; Graham and Weintraub, 1996). As soon as lower level abilities are fully mastered and can be executed automatically, more resources become available for higher level processes. Research on early handwriting acquisition suggests that the coordination of perceptual, motor, and cognitive processes is critical for efficient and fluent handwriting movements (Maldarelli et al., 2015).

The development of handwriting abilities starts even before entering school and prior to formal writing instructions on how to write letters, words and sentences, for example when children practice drawing or scribbling (Gombert and Fayol, 1992; Fischer and Wendler, 1994; Adi-Japha and Freeman, 2001). Children need to visually distinguish forms and symbols to be able to reproduce them accurately (Fischer and Wendler, 1994). Research with typically developing children has shown that between the ages of 6 and 7 the quality of handwriting develops rapidly which coincides with the start of formal writing instructions at school (Feder and Majnemer, 2007). Before the age of 10 the children's handwriting movements are slow and require graphomotor and visual feedback, only around the age of 14 years writing movements become fast and automatic, which releases more resources for higher level processes of writing (Huber and Headrick, 1999; Chartrel and Vinter, 2006; Pontart et al., 2013). The acquisition of writing is accompanied by a decrease in conscious attention to and control of the graphomotor execution, thus leading to an automatization of the writing process.

Previous research comparing adults' and children's writing abilities revealed that less skilled writers exhibit longer pauses between writing units and use more strokes to produce letters (Rosenblum et al., 2003, 2006; Sumner et al., 2013; Kandel and Perret, 2014; Julius and Adi-Japha, 2015). Experienced writers are able to plan their writing movements in advance and execute them more smoothly (shorter the time that the pen spends on the writing surface), compared to less skilled writers who rely more often on in air times of the pen tip between writing units for planning (longer time when the pen is above the writing surface; Julius and Adi-Japha, 2015). In an intervention study Julius and Adi-Japha (2015) revealed that kindergarten children improved strongest when compared to second graders and adults for writing time and for in air time in a point-to-point connection task to produce a letter-like symbol. A second study, by Kandel and Perret (2014), showed that even children between 8 and 10 years, who are in the middle of handwriting acquisition, already use the ability of *motor anticipation* to write fast and smoothly. Motor anticipation refers to the ability to write one letter while already processing information on how to produce the next letter. Through writing practice the children generate so-called motor programs that contain information on how the letters are shaped and the exact number, order and direction of the respective strokes (Meulenbroek and Van Galen, 1989; Kandel and Perret, 2014). This consolidation process requires years of practice and learning. As soon as the writer is able to activate the motor programs quickly and effortlessly the handwriting movements become automatic, continuous, and fast (Kandel and Perret, 2014). In the Kandel and Perret (2014) study children had to write letter sequences (*ll*, *le*, and *ln*) in cursive handwriting on a digitizer. The movement time of the up- and down-strokes indicated that motor anticipation of letter size changes (*ll* vs. *le*) and directional changes (*le* vs. *ln*) helped to reduce dysfluencies which decreased from 8 to 9 years and remained stable between 9 and 10 years. Dysfluent movements were mostly observed for down-strokes, which might suggest that the writer anticipated the motor sequence of the next letter.

Handwriting abilities can be divided into different dimensions, namely graphomotor, visuomotor, and handwriting. Regarding graphomotor abilities, studies have shown that it seems to be easier for children to draw horizontal lines to indicate spatial axes (e.g., the sky, the ground) than drawing vertical lines denoting depth of objects (Lange-Küttner, 1998). Even more difficult than vertical lines are diagonal lines that children acquire only at around 7 years of age (Laszlo and Broderick, 1991). A study by Meulenbroek and Van Galen (1986) showed that children between 6 and 9 years drew repetitive loops with a shorter duration and a higher velocity compared to zigzag lines.

Another important aspect of handwriting are visuomotor abilities. Visual-motor integration refers to the interaction of visual skills, visual-perceptual skills, and motor skills (Exner, 2010) and is known to play a crucial role in handwriting acquisition (Weil and Cunningham-Amundson, 1994; Tseng and Chow, 2000; Daly et al., 2003; Volman et al., 2006; Kaiser et al., 2009). Significant correlations between the results of the developmental test of Visual-Motor Integration (VMI; Beery and Beery, 2010) and the quality of handwriting are found such that children who achieve a higher score in visuomotor tasks write faster (Tseng and Chow, 2000) and have a better handwriting quality (Weil and Cunningham-Amundson, 1994; Cornhill and Case-Smith, 1996). As soon as the child can accurately copy the first 9 forms of the VMI he or she is ready to acquire handwriting (Weil and Cunningham-Amundson, 1994). To assess handwriting abilities of adults and children, previous studies usually used the alphabet writing task or the firstname-surname task (Pontart et al., 2013; Alamargot and Morin, 2015). In the alphabet task participants had to write the alphabet in the correct order in lower-case letters (Abbott and Berninger, 1993). For the firstname-surname task participants must write their own name repeatedly. Both tasks are supposed to mirror highly automatized writing movements that directly reflect handwriting abilities. However, both tasks introduce uncontrolled between-participants variability, because the letters in the alphabet are not ordered according to complexity in number or direction of strokes, and first names or surnames differ in the number, complexity and frequency of letters (Tim vs. Samantha).

Regarding handwriting abilities, research has mostly focused on examining the product of writing. The quality of handwriting was evaluated as the accuracy of letter formation, the uniformity of letter size, the spacing between letters and words, and the alignment on lines of writing (Hamstra-Bletz and Blöte, 1993). The assessment of quality is usually done by copying words or a sentence (e.g., "the quick brown fox jumps over the lazy dog") or by writing the alphabet in the correct order (Berninger et al., 1992, 1997; Graham and Weintraub, 1996; Medwell and Wray, 2014). However, these tasks can only be administered to children who have acquired writing skills (second grade or higher) and the rating of the above-mentioned categories is very subjective since there is no standard that would allow a comparison of the results between different age-groups. Furthermore, with the advent of new technologies researchers shifted to a more process-oriented approach to investigate handwriting (Rosenblum et al., 2003, 2006; Medwell and Wray, 2007; Tucha et al., 2008; Accardo et al., 2013; Gerth et al., 2016). These technologies provide an objective assessment of the dynamic subprocesses of handwriting (e.g., writing duration, in air time, writing velocity etc.; Marquardt and Mai, 1994; Tucha et al., 2008; Sumner et al., 2014; Gerth et al., 2016). Especially the number of inversions in velocity (NIVs) that describe the number of directional changes in velocity reflect how fluent and smooth handwriting movements are. Studies by Tucha et al. (2008; see also Tucha and Lange, 2005) have shown that directing attention to the writing movements increased the NIVs and hampered the automaticity of handwriting performance (even in adults). Thus, we believe that NIVs are an adequate and objective handwriting measure to quantify the level of automaticity in graphomotor execution and the amount of directed attention to the writing process.

Concering the comparison of the two writing surfaces—tablet and paper—a recent review article by Wollscheid et al. (2016) identified merely ten articles that compare the impact of writing tools (computer keyboards and tablet) vs. non-digital writing tools (pen and paper) on primary school students. The authors included studies that were published between 2005 and February 2015. Seven of the studies compared handwriting with typing. Only one article (Read et al., 2005) actually compared writing with a pen on a graphic tablet to using pencil and paper (and typing as a third condition). The 7 to 8 year old students wrote a story for about 12 min and were then given 2 min to edit their work. The stories were rated according to quality (teacher assessed) and quantity of writing (word count). However, this way of comparing the two media—tablet and paper—is quite product-oriented and cannot grasp the dynamics of graphomotor execution during writing on the two writing surfaces.

Only a few studies systematically investigated the question whether there is a difference between writing on a tablet and on paper. Alamargot and Morin (2015) studied second and ninth graders who wrote the alphabet and their own names on a tablet and on paper. Their results show that both groups wrote their names less legible and letter size was larger for both tasks on the tablet. The two groups were influenced differently by the two writing surfaces. The ninth graders showed faster writing speed and higher pen pressure whereas the second graders exhibited more pauses during writing on the tablet. A second study by Gerth et al. (2016) compared handwriting performance of adults on a tablet and on paper. Their findings reveal differences between writing on the two media that were partly modulated by the writing task. Even experienced writers, such as most adults, were influenced by the difference in friction between the writing surfaces. Interestingly, adults were able to adapt their graphomotor execution quickly to the smoother surface of the tablet by modulating their pen pressure and enlarging the writing size. Yet, there is no research that compared handwriting performance of participants without prior writing instruction (preschoolers) with that of beginning writers (second graders) and experienced writers (adults).

The Present Study

The aim of the present study is to determine whether there are general and task-related effects of different levels of automaticity during writing on a tablet and on paper. To reach a comprehensive understanding of different levels of handwriting performance we chose the following three tasks with differing task demands assessing (1) graphomotor abilities—using continuous and repetitive patterns that participants had to copy, (2) visuomotor abilities—using a standardized test for which participants had to copy geometric forms and (3) automatic handwriting abilities—using a word-copying task. For all three tasks we evaluated handwriting quality (writing product) and handwriting dynamics (writing process). Measures of handwriting quality reflect influences of the writing surface on the handwriting performance, which are immediately visible to the writer. In contrast, the handwriting dynamics reflect subconscious motor and cognitive processes that can only be detected through handwriting measures recorded by the tablet. Further, we wanted to capture different levels of handwriting automaticity to investigate whether group differences could be due to a distinct adaptation to the smoother and unfamiliar writing surface (i.e., the tablet). Until now handwriting development research has focused on comparing adults' and children's handwriting performance. We added the group of preschoolers with very basic handwriting skills and conducted the study with three participant groups with different levels of handwriting automaticity (preschoolers, second graders, and adults). We expected that preschoolers perform worse regarding the handwriting quality and with lower automaticity in handwriting dynamics in all tasks compared to the second graders and adults. We predicted similar results for the second graders' handwriting performance compared to the one of the adults'. Taken together, we used a wide-ranging set of tasks to obtain a comprehensive picture on different dimensions of handwriting and to explore task-dependent adaptations to the writing surface. Handwriting quality and dynamics might be modulated by the participant's experience with writing on the tablet or paper and by the participant's level of handwriting automaticity.

METHODS AND MATERIALS

Participants

To capture the development in handwriting, we recruited three groups with varying levels of handwriting automaticity. Twenty-five preschoolers [17 female, mean age 5.4 years (*SD*: 0.6)] and 27 children in second grade [14 female, mean age 7.7 years (*SD*: 0.5)] were tested in this study. The preschoolers were recruited from three different kindergartens in Potsdam and the second graders from a day care center in Potsdam. The presented study also included a control group of 25 adults [21 female, mean age 21.8 years (*SD*: 2.6)] taken from an earlier study (Gerth et al., 2016). All participants were right-handed German native speakers and naïve to the purpose of the study. They had normal or corrected-to-normal vision. The parents of the children were informed about the study in an information letter and gave their written informed consent for the participation of their children. The study was approved by the ethics committee of the University of Potsdam (Reference number 41/2014) and it was conducted in accordance with the ethical standards laid down in the Declaration of Helsinki.

Procedure

We conducted the study in two conditions: (1) writing with a Lenovo Pen on a ThinkPad X61 and (2) writing on a sheet of paper with an Intuous Inking Pen. To obtain the same handwriting measures as in condition (1) we placed the paper on a digitizer (Intuos4 XL DTP) and the digitizer was connected via an USB cable to a ThinkPad X61 (henceforth tablet). We could thus record performances with the same temporal and spatial resolution in both conditions. The digitizer and the tablet have tarnished plastic surfaces. The paper has a density of 80 g/m^2. In order to level the height of the tablet with the forearm of the participant's writing hand we used a wooden frame (width: 62 cm, length: 46 cm, height: 3 cm). We set the sampling frequency of both devices to 133 Hz using the Wacom© software. The acquisition software was programmed in C# and XAML using Visual Studio Community 2013 Update 4 and the Windows Presentation Foundation runtime libraries provided by the Microsoft .NET Framework 4.5© Microsoft. In the methods study by Gerth et al. (2016) the friction of the two writing surfaces was quantified in an experimental set-up. The results showed that the friction of the paper surface was higher compared to the tablet surface (mean in writing velocity paper: 17.91 mm/s, tablet: 35.15 mm/s).

The preschoolers were tested individually in a quiet room in the kindergarten and the second graders in a silent room in the day care center. The adults' control group was tested in a silent laboratory at the University of Potsdam. All participants sat in a chair adjusted to their height in front of a table on which we positioned the tablet or paper on a digitizer. Half of the participants in each group started with condition (1), the other half with condition (2). Before the actual experiment, participants were familiarized with the medium by writing their first name and drawing circles around a dot. To prevent any bias from handedness the experimenter placed the pen in the middle of the tablet in front of each participant. Only right-handed participants were included in the study to prevent distorted results due to handedness. One session took approximately 20 min for all participants. The time between sessions varied between 2 and 19 days.

Materials

We used three different tasks (used also by Gerth et al., 2016) measuring (a) graphomotor abilities, (b) visuomotor abilities, and (c) handwriting abilities (copying the phrase "Sonne und Wellen" [German for "sun and waves"]). Each task was performed twice by each participant, once on a tablet with a pen and in another session on paper attached to a tablet. We kept the writing space and the order of tasks parallel in both sessions.

Graphomotor Abilities

In order to investigate graphomotor abilities we used four continuous and repetitive movement patterns: (1) loop patterns without constraints (**Figure 1A**), (2) loop patterns around dots (**Figure 1B**), (3) zigzag lines (**Figure 1C**), and (4) staircase patterns (**Figure 1D**). For the first task, the experimenter drew the loop pattern and the participant had to copy the movement on the next screen (**Figure 1A**). For all other tasks the pattern to copy was given in the upper half of the screen and the participant copied the pattern below. Each pattern was produced twice by the participant. The writing space for all four tasks had a size of 24.7×8.5 cm.

Visuomotor Abilities

We were further interested in those visuomotor abilities that are known to predict handwriting measures. Therefore, we selected two tasks of the standardized test of visuomotor abilities, the Beery-Buktenica Developmental Test of Visual-Motor Integration (VMI) 6th Edition (Beery and Beery, 2010). This test is child-friendly and captures how visual perception and finger-hand movements are coordinated in children and adults, e.g., during handwriting (Volman et al., 2006). We used the first 9 items of the VMI and the Motor Coordination (MC) tasks because these forms can be mastered even by children who cannot write (Weil and Cunningham-Amundson, 1994). Since we tested preschool children without any prior instruction in writing this was an important criterion for item selection. The first 9 forms in both tasks (VMI and MC) are identical. We created a digital version of both tests to be able to track the handwriting process on a tablet.

For the first task, the VMI, participants had to copy geometric forms (**Figure 2A**) that were shown in the upper half of the screen (in groups of three items) into a square directly below (**Figure 2C**). Similarly, in the second task, the MC, participants traced a geometric form (**Figure 2B**) by connecting the dots (starting at the black dot) without crossing the double-lined path. The figures to be copied were presented in the upper half of the screen in a smaller scale which is in accordance with the guidelines of the standardized test (**Figure 2D**). Each square for both tasks had a size of 7.5×7.5 cm.

Handwriting Abilities

Lastly, we investigated the process of writing the phrase "Sonne und Wellen" (German, in English "sun and waves"). This task was only administered with two participant groups, the second graders, and the adults, since the preschoolers had no prior writing instruction and could therefore not complete this writing task. The participants copied the phrase 10 times on given lines in their own handwriting speed. We did not constraint the type of handwriting—printed or cursive. The printed phrase was presented at the top of the screen to prevent any bias due to the participants' memory capacity (**Figure 3**). The lines were 15 cm long and the space between the lines was 2.4 cm (100 px).

Data Analysis

To evaluate the handwriting product, we ran linear models on the error points (dependent variable) for each task with the factor Medium (tablet vs. paper) and the factor Group (preschool, second grade, adults) for the between-group comparisons using the software R version 3.0.1 (R Development Core Team, 2013).

For the analysis of the handwriting process measures, the *x*- and *y*-coordinates of the pen were recorded together with the time with a sampling frequency of 133 Hz. We smoothed the resulting velocity profiles by implementing the non-parametrical kernel estimation devised by Marquardt and Mai (1994) with the help of R-scripts (R version 3.0.1, R Development Team Core Team 2013). Then we computed the writing velocity by taking the first derivative of the *x*- and *y*-coordinates with respect to time. To obtain the number of inversions in velocity (NIVs) we calculated the sum of all NIVs per item. NIVs are sometimes calculated as the sum per up-stroke and down-stroke (Tucha et al., 2008). However, we changed this to the sum of all NIVs for one item because we did not exclusively test the writing of words.

We performed a standard outlier adjustment of the data based on the handwriting process measures by excluding data that were 3 standard deviations (*SD*'s) above the group mean for all handwriting measures (listed in Section Handwriting Process Measures). These data were mainly due to technical problems, misunderstandings of the instructions or other external factors. Additionally for writing velocity we excluded data 3 *SD*'s below the group mean. For the VMI and MC task the item complexity varied substantially, hence we excluded data based on the mean of the item instead of the group mean. In total we excluded 5.2% for the paper condition (preschool children: 6.6%, second graders: 5.9% and adults: 3.3%) and 5.2% for the tablet condition (preschool children: 4.8%, second graders: 6.1% and adults: 3.8%). In a next step we excluded a data point in the data set for the tablet condition if it had previously been removed for the paper condition and the other way around, because we were interested in the direct comparison of the two writing surfaces. Thereby we could apply repeated-measures for the statistical analyses without any problems due to missing data. In total we excluded 9.4% of the data.

We analyzed each task separately by applying linear mixed-effect models with repeated measures using the function lme() provided by the software R version 3.0.1 (R Development Core Team, 2013) and the nlme-package (Pinheiro et al., 2014). For each handwriting measure (dependent variable) we ran a separate model. The independent variables were the factor Medium (tablet vs. paper) and for the group-comparison the factor Group (preschool, second grade, adults). The models were fit using the maximum likelihood method (method = "ML") and participants were used as random factors within the factor Medium (random = 1|∼Participant/Medium). We log-transformed the writing duration and the in air time in order to avoid skewed distributions.

Handwriting Product Evaluation

To evaluate the quality of the produced items we scored the results of the tasks visually. The standardized tasks VMI and MC were evaluated according to the manual of the Beery-Buktenica Developmental Test of Visual-Motor Integration 6th Edition (Beery and Beery, 2010). Each geometric form was quantified by two raters (1—correctly copied item, 0—incorrectly copied item)

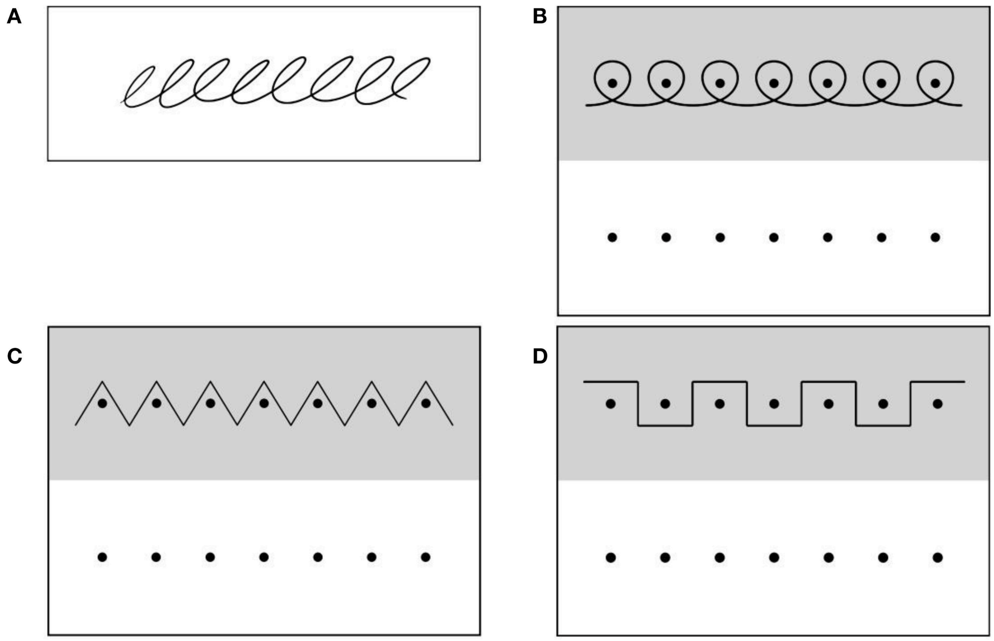

FIGURE 1 | Instruction (A): Copy the loop pattern on the next screen. (B–D) Copy the pattern above in the space below. Reprinted from Gerth et al. (2016) with permission from Elsevier.

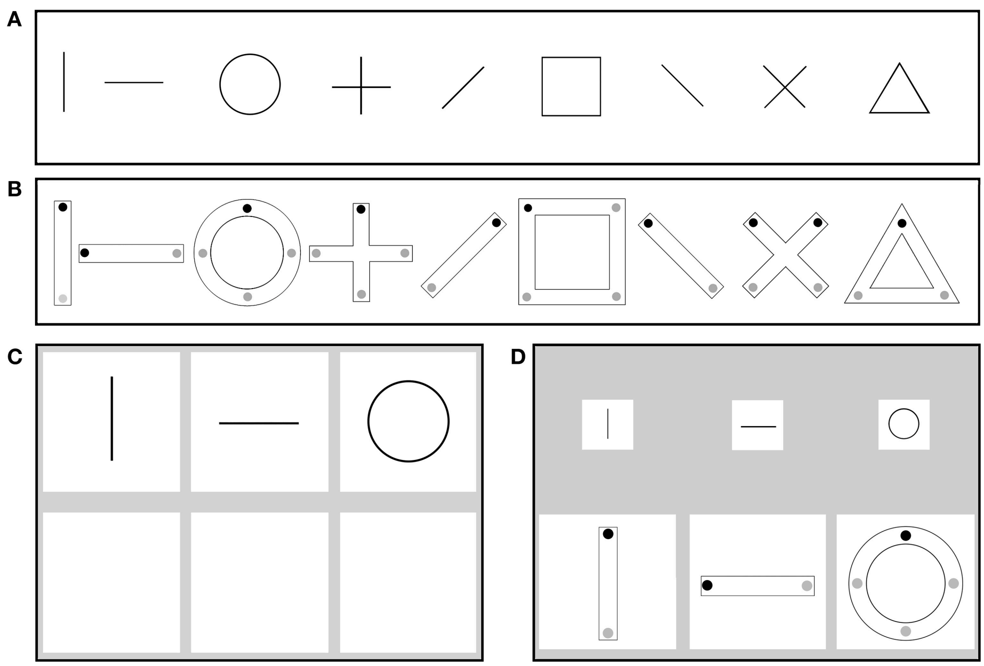

FIGURE 2 | The first nine forms of the Visual-Motor Integration task (A) and the Motor Coordination task (B) (Beery and Beery, 2010). The writing space of the VMI **(C)** and the MC **(D)**. Reprinted from Gerth et al. (2016) with permission from Elsevier.

and the total score quantifies how accurately the participants copied the forms.

For the graphomotor and the handwriting abilities task we created a scoring scheme that was inspired by the standardized Minnesota Handwriting Assessment, MHA (Reisman, 1999). We used 5 error categories for the graphomotor abilities and 4 error categories for the handwriting abilities. The 5 error categories for graphomotor abilities were: (1) pen lift during the task, (2) overlapping loops, (3) the lowest point of a loop is drawn lower than the highest point of any other loop (which means

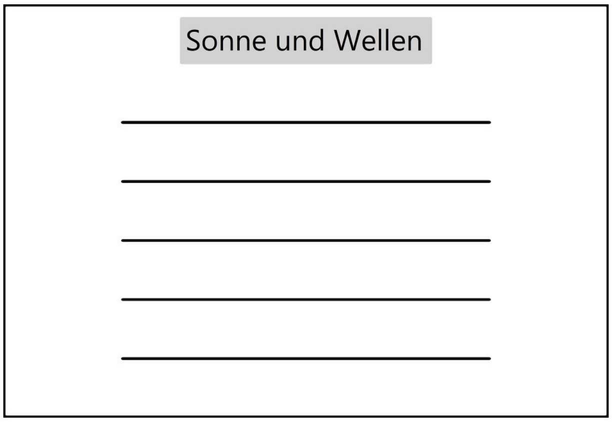

FIGURE 3 | The writing space for "Sonne und Wellen" (German, English "sun and waves"). Reprinted from Gerth et al. (2016) with permission from Elsevier.

that the loops had to be drawn in a horizontal orientation), (4) a loop is unrecognizable, and (5) upside-down loops. To quantify the quality of the handwriting abilities task we created a similar rating scheme with 4 error categories: (1) legibility, (2) shape, (3) alignment in relation to the base line, and (4) spacing between letters. Each symbol (e.g., loop) and each letter (of "Sonne und Wellen") was rated separately in each of the 5 error categories. For the handwriting task there are 14 letters in total for one item. The rater scored the legibility for each of the 14 letters and counted how often an error of legibility occurred. If a participant made 3 legibility errors, then 3 was divided by 14 (maximum of letters) to obtain the total error points score for legibility of this item (=0.21). This scoring procedure was applied to all 4 error categories for the handwriting abilities. If there was no error in one of the categories the score was set to 0. In the end the scores of the error categories were summed up and divided by 4 (=total number of error categories for handwriting abilities) to obtain the total error score for an item (with two decimal places). We used the same scoring scheme for loops without dots (maximum number of loops was equal to the number of loops drawn), loops with dots (maximum number of loops: 7), zigzag lines (maximum number of triangles: 7), and the staircase pattern (maximum number was set to number of possible strokes: 13).

Handwriting Process Measures

To evaluate the handwriting process we calculated the following handwriting measures.

Writing duration: the time in milliseconds (ms) that the pen is on the surface of the tablet or paper (pressure > 0). This gives an indication of temporal performance and is linked to average velocity (Rosenblum et al., 2003).

Writing velocity: in millimeter per second (mm/s). This measure is used to evaluate the fluidity in handwriting performance (Rosenblum et al., 2003).

In air time: the time in ms that the pen is above the surface (distance < 1 cm). This measure indicates breaks in writing and might be linked to higher level processes (Rosenblum et al., 2003; Sumner et al., 2013).

Number of strokes: determines continuous movements until the pen is lifted from the surface (pressure $= 0$). A large number of strokes might reveal irregular and non-automatized writing (Tucha et al., 2008).

Number of inversions in velocity (NIV): indicate the degree of handwriting automaticity and are related to the number of accelerations and decelerations during writing. While low NIVs characterize an automatized and smooth movement, higher NIVs are associated with a lesser degree of automaticity, for instance when adults are asked to mentally track their own handwriting movements (Marquardt et al., 1996; Tucha et al., 2008).

RESULTS

At first we will present the results of our visual evaluation of the quality of the produced items (Section Handwriting Product Evaluation) and then examine the results of the handwriting process measures (Section Handwriting Process Measures). For both parts we will firstly review the results of the comparison between the two surfaces (tablet vs. paper) to show differences in graphomotor execution between the media and secondly the results for the between-group analyses to investigate differences in the level of handwriting acquisition.

Handwriting Product Evaluation

Graphomotor Abilities

Table 1 presents a summary of the data and statistical effects for our scoring of the handwriting products for each of the tasks. Regarding the graphomotor abilities we found differences between the execution on the tablet and paper for loops with dots only for the preschool children ($p = 0.048$) such that they obtained more error points on the tablet compared to paper. For zigzag lines all groups showed differences between the two writing surfaces (preschool: $p < 0.001$; second grade: $p < 0.001$; adults: $p = 0.039$), the preschoolers and second graders received more error points in the tablet condition while the adults showed the opposite pattern with more error points for the paper condition. For the last task, the staircase pattern, only the adults showed a significant difference between the media ($p < 0.001$) with more error points when executing the task on paper compared to on the tablet.

The results of between-group analyses show that preschoolers obtained more error points compared to adults for all four graphomotor ability tasks (all $p < 0.001$; loops without dots $b = -0.038$, loops with dots $b = -0.067$, zigzag lines $b = -0.069$, staircase pattern $b = -0.038$) and preschoolers produced more error points than second graders for loops without dots ($p < 0.001$, $b = 0.104$), loops with dots ($p < 0.001$, $b = -0.071$), and zigzag lines ($p < 0.001$, $b = -0.071$). The comparison of second graders and adults yielded a significantly worse performance for second graders only for the staircase pattern ($p < 0.001$, $b = 0.043$). Additionally we obtained significant interactions between the factor Medium (tablet vs. paper) and Group (preschool, second grade, adults) for three of the tasks: (1) for loops with dots between preschoolers and adults ($p = 0.022$,

TABLE 1 | Means and standard deviations in parentheses for the scoring of the handwriting product.

	Preschool	Second grade	Adults
LOOPS WITHOUT DOTS—ERROR POINTS			
Paper	0.175 (0.134)	0.072 (0.112)	0.042 (0.017)
Tablet	0.186 (0.114)	0.077 (0.038)	0.039 (0.018)
p-value	0.695	0.756	0.498
b-value	0.010	0.005	−0.002
LOOPS WITH DOTS—ERROR POINTS			
Paper	0.132 (0.099)	0.061 (0.032)	0.034 (0.012)
Tablet	0.204 (0.232)	0.078 (0.059)	0.038 (0.014)
p-value	0.048*	0.066	0.079
b-value	0.072	0.017	0.005
ZIGZAG LINES—ERROR POINTS			
Paper	0.148 (0.070)	0.078 (0.046)	0.072 (0.068)
Tablet	0.197 (0.051)	0.186 (0.072)	0.051 (0.023)
p-value	<0.001*	<0.001*	0.044*
b-value	0.049	0.109	−0.021
STAIRCASE PATTERN—ERROR POINTS			
Paper	0.064 (0.054)	0.052 (0.034)	0.095 (0.039)
Tablet	0.071 (0.033)	0.054 (0.029)	0.064 (0.017)
p-value	0.463	0.741	<0.001*
b-value	0.007	0.002	−0.031
VISUAL MOTOR INTEGRATION (VMI)—ACCURACY IN %			
Paper	92.9 (25.8)	99.6 (6.2)	100 (0)
Tablet	85.0 (35.7)	96.5 (18.3)	99.6 (6.7)
p-value	<0.001*	0.011*	0.318
b-value	−0.078	−0.031	−0.004
MOTOR COORDINATION (MC)—ACCURACY IN %			
Paper	94.7 (22.5)	98.9 (10.7)	100 (0)
Tablet	85.5 (35.3)	91.6 (27.8)	98.7 (11.5)
p-value	<0.001*	<0.001*	0.083
b-value	−0.092	−0.073	−0.013
WRITING "SUN AND WAVES"—ERROR POINTS			
Paper	–	0.116 (0.094)	0.125 (0.109)
Tablet		0.125 (0.085)	0.165 (0.122)
p-value		0.220	<0.001*
b-value		0.010	0.040

The p-value refers to the comparison for Medium (tablet vs. paper). The b-value refers to the regression coefficient of the tablet condition in comparison to paper. The asterisk indicates significant effects below an alpha-level of 0.05.

$b = -0.067$; preschoolers showed a difference in error points between paper and tablet while there was no such difference for the adults), (2) for zigzag lines between preschoolers and adults ($p < 0.001$, $b = -0.069$) as well as second graders and adults ($p < 0.001$, $b = -0.129$; adults exhibited more error points on paper but preschoolers and second graders produced more error points on the tablet) and between preschoolers and second graders ($p < 0.001$, $b = 0.060$; second graders obtained a larger increase in error points between tablet and paper than preschoolers), and (3) for the staircase pattern between preschoolers and adults ($p < 0.001$, $b = -0.383$) as well as second graders and adults ($p < 0.001$, $b = -0.033$; adults showed a significant difference in error points between tablet and paper whereas preschoolers and second graders did not). **Figure 4** visualizes the significant interactions (2) and (3).

Visuomotor Abilities

Two raters evaluated the visuomotor ability tasks, VMI and MC, according to the test manual (Beery and Beery, 2010). The accuracy data describes how accurately the participants copied the geometric forms (VMI) or traced the geometric forms without crossing the double-lined path (MC). The comparison between tablet and paper yielded differences only for the children groups for the VMI (preschool: $p < 0.001$; second grade: $p = 0.011$) as well as the MC (preschool: $p < 0.001$; second grade: $p < 0.001$) such that both groups showed a better performance (fewer error points) on paper compared to the tablet condition for both tasks. The adults were at ceiling performance and exhibited no differences between the two media.

The between-group analyses revealed differences in group performances for both tasks (VMI and MC) between preschoolers and adults (VMI: $p < 0.001$, $b = -0.074$; MC: $p = 0.009$, $b = 0.053$) as well as between preschoolers and second graders (VMI: $p < 0.001$, $b = -0.067$; MC: $p = 0.033$, $b = -0.042$) mirroring the fact that preschoolers performed less accurate than second graders and adults; additionally second graders were less accurate than adults in both tasks. Furthermore, we found significant interactions between Medium (tablet vs. paper) and Group (preschool, second grade, adults) for both tasks. For VMI the interaction was significant between preschoolers and adults ($p = 0.005$, $b = -0.074$) meaning that we did not find a difference in accuracy between-media for adults but for preschoolers. For MC the analyses revealed two interactions: one between preschoolers and adults ($p = 0.006$, $b = 0.079$) and a second one between second graders and adults ($p = 0.033$, $b = 0.059$) showing that both children groups exhibited significant differences in performance on the tablet and on paper whereas the adults showed no such between-media difference in accuracy.

Handwriting Abilities

The results of writing the phrase "Sonne und Wellen" showed differences between writing on paper vs. on the tablet only for the adults' group ($p < 0.001$) who wrote less well on the tablet than on paper. The performance of the second graders was not significantly different between the media ($p = 0.220$) but pointed into the same direction as the results of adults.

When comparing the second graders' performance to that of the adults we found only a significant interaction between Medium (tablet vs. paper) and Group (second grade, adults; $p = 0.016$, $b = -0.031$) mirroring the fact that adults showed a difference in error points between tablet and paper whereas the second graders exhibited no such difference.

Handwriting Process Measures

Graphomotor Abilities

Table 2 presents the descriptive data and statistical effects for the writing measures of the graphomotor abilities for the three groups. We will review the results in the order of the writing measures.

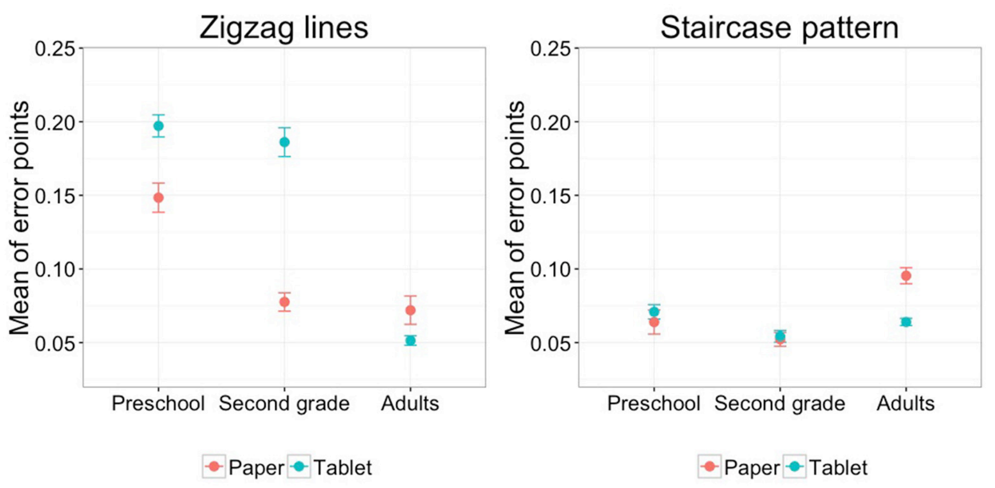

FIGURE 4 | The significant interaction between medium and group for the error points of zigzag lines and the staircase pattern (with standard errors).

The writing duration was longer on paper than on tablet for loops without dots for the preschool children ($p = 0.012$), for loops with dots for the adults ($p = 0.026$), and for zigzag lines for the two children groups (preschool: $p = 0.025$; second grade: $p = 0.039$). Regarding in air time we found longer in air times for the paper condition than in the tablet condition for loops without dots for the preschool children ($p = 0.039$)[1]. Similarly we found more pen lifts for the paper condition compared to the tablet condition for loops without dots for the preschool children ($p = 0.038$) and for the staircase pattern the second graders lifted the pen more often in the tablet condition compared to paper ($p = 0.033$). The writing velocity was higher on the tablet than on paper for all tasks and all groups (all $p < 0.026$) except for the staircase pattern in the preschool children ($p = 0.114$). There were significantly fewer NIVs in the tablet condition compared to paper for loops without dots in all groups (preschool: $p = 0.005$; second grade: $p = 0.024$; adults: $p = 0.021$), for loops with dots only in the preschool group ($p = 0.039$), for zigzag lines in both children groups (preschool: $p = 0.005$; second grade: $p = 0.015$), and for the staircase pattern only in the adults group ($p = 0.047$).

Earlier research found that a smoother handwriting movement (=higher velocity) is associated with fewer NIVs (=more automatized and smoother movement; Meulenbroek and Van Galen, 1990; Gerth et al., 2016), therefore we computed Kendall's tau correlations[2] between writing velocity and NIVs. For all four tasks and all three groups these two handwriting measures were negatively correlated, meaning that a smoother movement produced fewer NIVs (all $p < 0.001$; loops without dots: preschool $\tau = -0.66$, second grade $\tau = -0.58$, adults $\tau = -0.33$; loops with dots: preschool $\tau = -0.67$; second grade $\tau = -0.63$; adults $\tau = -0.62$; zigzag lines: preschool $\tau = -0.53$; second grade $\tau = -0.57$; adults $\tau = -0.59$; staircase pattern: preschool $\tau = -0.71$; second grade $\tau = -0.61$; adults $\tau = -0.68$).

[1]We did not run analyses on *in air time* and *number of pen lifts* if *in air time* was 0ms or the *number of pen lifts* was equal to 1.

[2]We used Kendall's tau correlations because the handwriting measures were not normally distributed.

Results of the between-group analyses for writing duration revealed for all four tasks that preschoolers wrote longer than adults (all $p < 0.001$, loops without dots $b = -0.846$, loops with dots $b = -0.600$, zigzag lines $b = -0.373$, staircase pattern $b = -0.463$) and preschoolers wrote longer than second graders for loops without dots ($p = 0.034$, $b = -0.252$) and loops with dots ($p = 0.033$, $b = -0.193$) as well as second graders wrote longer than adults for all four tasks (all $p < 0.001$, loops without dots $b = -0.594$, loops with dots $b = -0.408$, zigzag lines $b = -0.331$, staircase pattern $b = -0.431$). For in air time we found that for loops without dots, loops with dots and zigzag lines preschoolers lifted the pen longer than adults (all $p < 0.008$, loops without dots $b = -2.351$, loops with dots $b = -2.002$, zigzag lines $b = -2.077$) and second graders produced longer in air times than adults for loops without dots ($p = 0.011$, $b = -1.552$) and loops with dots ($p = 0.003$, $b = -2.439$). We also found significant interactions for in air time between Medium (tablet vs. paper) and Group (preschool, second grade, adults) for loops without dots between preschoolers and adults ($p = 0.036$, $b = 1.789$; preschoolers show a significant difference between tablet and paper while there was no difference for adults) and for zigzag lines between preschoolers and second graders [$p = 0.007$, $b = 2.333$; preschoolers exhibited numerically longer in air times for paper whereas second graders produced (numerically) longer in air times in the tablet condition]. For number of pen lifts we found that preschoolers lifted the pen more often than adults for all four tasks (all $p < 0.05$, loops without dots $b = -0.833$, loops with dots $b = -0.525$, zigzag lines $b = -0.761$, staircase pattern $b = -0.574$), preschoolers produced more pen lifts than second graders for loops without dots ($p = 0.019$, $b = -0.500$) and for zigzag lines ($p = 0.015$, $b = -0.511$). Additionally, we found significant interactions for loops without dots between preschoolers and adults ($p = 0.008$, $b = 0.762$; preschoolers showed a difference in pen lifts between the two writing surface whereas the adults did not lift the pen for either of the two) and between preschoolers and second graders ($p = 0.027$, $b = 0.658$;

preschoolers show a significant difference in the number of pen lifts between tablet and paper whereas the second graders showed no difference), as well as for zigzag lines between preschoolers and adults ($p = 0.026$, $b = 0.696$; preschoolers lifted the pen numerically more often for paper whereas the adults showed no difference between media) and between preschoolers and second graders ($p = 0.010$, $b = 0.779$; preschoolers lifted the pen numerically more often for paper whereas second graders produced more pen lifts for the tablet). For writing velocity we found that preschoolers wrote significantly slower than adults for loops without dots ($p < 0.001$, $b = 59.970$) and loops with dots ($p < 0.001$, $b = 12.235$), further preschoolers wrote slower than second graders for loops without dots ($p = 0.010$, $b = 18.546$), and second graders wrote slower than adults for loops without dots ($p < 0.001$, $b = 41.424$), loops with dots ($p = 0.022$, $b = 9.260$), and the staircase pattern ($p = 0.002$, $b = 6.964$). For the NIVs we found that preschoolers produced significantly more NIVs than adults for all tasks ($p < 0.001$, loops without dots $b = -42.792$, loops with dots $b = -52.080$, zigzag lines $b = -23.630$, staircase pattern $b = -31.089$); preschoolers also produced more NIVs than second graders for loops without dots ($p = 0.026$, $b = -16.473$) and loops with dots ($p = 0.002$, $b = -21.946$) and second graders produced more NIVs than adults for all four tasks (all $p < 0.001$, loops without dots $b = -26.319$, loops with dots $b = -30.134$, zigzag lines $p = -18.500$, staircase pattern $b = -28.689$). Furthermore, we found significant interactions for Medium and Group between preschoolers and adults for loops without dots ($p = 0.018$, $b = 21.842$; preschoolers showed a bigger difference between the writing surfaces than the adults and performed worse than adults) and zigzag lines ($p = 0.012$, $b = 11.565$; preschoolers exhibited a difference in NIVs between tablet and paper whereas the adults showed no such difference). We illustrate these interactions between Medium and Group in **Figure 5**.

Visuomotor Abilities

Table 3 shows a summary of the data and statistical effects for the handwriting measures of the VMI and MC tests. Only the adults wrote significantly longer on the computer compared to paper for the MC ($p = 0.028$). The writing velocity was higher on the tablet for all groups for the VMI (preschool: $p < 0.001$; second grade: $p = 0.002$; adults: $p < 0.001$). For the MC we found a higher writing velocity on the tablet only for the children groups (preschool: $p < 0.001$; second grade: $p = 0.037$). Regarding the NIVs only the preschool children produced more NIVs on paper compared to the tablet ($p = 0.030$).

The correlation analyses between writing velocity and NIVs revealed an inverse relationship between these two measures (all $p < 0.001$; VMI: preschool $\tau = -0.37$, second grade $\tau = -0.39$, adults $\tau = -0.40$; MC: preschool $\tau = -0.38$, second grade $\tau = -0.39$, adults $\tau = -0.34$).

The between-group analyses of writing duration revealed for the MC that preschoolers wrote longer than adults ($p < 0.001$, $b = 0.445$) and longer than second graders ($p < 0.001$, $b = 0.425$). Further the interaction between Medium (tablet vs. paper) and Group was significant for the MC between preschoolers and adults ($p = 0.016$, $b = -0.204$; preschoolers show no difference between the two writing surfaces whereas adults wrote longer on the tablet than paper). There were no significant effects for in air time. For the number of pen lifts we found for the VMI that preschoolers lifted the pen less often than adults ($p = 0.003$, $b = 0.134$) and more often than the second graders ($p = 0.003$, $b = -0.177$). For writing velocity we found for the MC that preschoolers and second graders wrote faster than adults (both $p < 0.001$, preschoolers vs. adults $b = -6.212$, second graders vs. adults $b = -6.126$). Further we found an interaction for the MC between preschoolers and adults ($p = 0.002$, $b = 3.720$; preschoolers wrote faster on the tablet whereas adults show no difference between the writing surfaces). For NIVs we found for the MC that preschoolers and second graders produced more NIVs than adults (both $p < 0.001$, preschoolers vs. adults $b = 11.160$, second graders vs. adults $b = 11.242$).

Both tasks contained the same set of items, therefore we conducted additional analyses with the factor Task (VMI vs. MC) to check directly for task differences in graphomotor demands. We found a main effect for Medium (tablet vs. paper) for writing velocity in all groups (preschool: $p < 0.001$, $b = 6.361$; second grade: $p = 0.003$, $b = 6.279$; adults: $p < 0.002$, $b = 3.482$) and for NIVs for preschool children ($p = 0.020$, $b = -2.222$). The factor Task yielded significant differences between VMI and MC for all writing measures for the preschoolers (writing duration: $p < 0.001$, $b = 0.908$, pause duration: $p = 0.001$, $b = 0.695$, number of pen lifts: $p = 0.001$, $b = 0.155$, velocity: $p < 0.001$, $b = -21.534$, NIVs: $p < 0.001$, $b = 16.077$) and second graders (writing duration: $p < 0.001$, $b = 0.852$, pause duration: $p = 0.002$, $b = 0.635$, number of pen lifts: $p < 0.001$, $b = 0.155$, velocity: $p < 0.001$, $b = -20.415$, NIVs: $p < 0.001$, $b = 15.005$) and for writing duration ($p < 0.001$, $b = 0.453$), velocity ($p <= 0.001$, $b = -10.643$) and NIVs ($p < 0.001$, $b = 5.465$) in the adult group. For the MC (compared to the VMI) participants wrote longer and slower and produced more NIVs. Additionally, the children groups lifted the pen for a longer time and more often for the MC than the VMI. The interaction between Medium and Task was significant for writing velocity for all groups ($p < 0.001$, preschoolers $b = -9.076$, second graders $b = -9.077$, adults $b = -7.060$) such that participants wrote faster on the tablet than on paper for the VMI, but there was no difference for the MC for the adult group and a smaller difference for velocity between-media for the children groups.

Handwriting Abilities

Table 4 presents a summary of the data and statistical effects for the handwriting measures of writing the phrase "Sonne und Wellen." We administered this task only to the second graders and adults because the preschoolers were not capable of writing words. We found longer writing durations on the tablet compared to paper for both groups (both $p < 0.001$). Only adults showed a longer in air time on the tablet ($p = 0.002$) and more pen lifts on paper ($p = 0.031$). Both groups exhibited a higher velocity on the tablet compared to paper (both $p < 0.001$). For the NIVs only adults produced more NIVs on the tablet than on paper ($p = 0.010$).

TABLE 2 | Means and standard deviations in parentheses for writing measures of the graphomotor abilities.

	Writing duration (ms)	In air time (ms)	Number of pen lifts	Velocity (mm/s)	NIVs
LOOPS WITHOUT DOTS					
Preschool					
Paper	11918.97 (5832.35)	394.29 (1054.81)	1.69 (1.32)	41.40 (20.29)	76.94 (41.51)
Tablet	8741.83 (3988.76)	37.20 (181.56)	1.06 (0.24)	54.78 (22.61)	52.46 (26.18)
p-value	0.012*	0.039*	0.038*	0.026*	0.005*
b-value	−0.305	−1.789	−0.762	12.264	−24.762
Second grade					
Paper	9548.36 (5591.74)	127.50 (358.57)	1.36 (0.79)	59.21 (25.31)	60.43 (34.95)
Tablet	6696.05 (2497.08)	128.81 (307.44)	1.19 (0.40)	80.49 (20.93)	40.64 (14.84)
p-value	0.077	0.638	0.524	0.014*	0.024*
b-value	−0.239	0.370	−0.104	17.825	−18.875
Adults					
Paper	4760.90 (1273.86)	0	1	104.55 (36.75)	34.88 (7.46)
Tablet	4549.95 (934.84)	0	1	125.06 (31.97)	32.30 (5.75)
p-value	0.216	–	–	<0.001*	0.021*
b-value	−0.047	–	–	23.979	−2.920
LOOPS WITH DOTS					
Preschool					
Paper	15487.32 (5731.07)	355.86 (1012.18)	1.43 (1.04)	28.64 (10.78)	95.84 (37.34)
Tablet	13698.38 (4273.72)	314.38 (570.60)	1.49 (0.80)	37.24 (11.94)	78.68 (25.40)
p-value	0.226	0.226	0.909	0.011*	0.039*
b-value	−0.108	1.066	0.025	8.130	−17.300
Second grade					
Paper	12883.36 (4278.60)	157.79 (302.76)	1.30 (0.55)	31.47 (13.97)	75.49 (28.41)
Tablet	11376.30 (3010.24)	276.87 (620.24)	1.38 (0.74)	41.80 (14.93)	63.91 (19.20)
p-value	0.173	0.980	0.499	0.001*	0.125
b-value	−0.091	−0.022	0.096	9.984	−10.038
Adults					
Paper	8168.95 (2420.36)	0	1	43.03 (16.07)	43.36 (12.50)
Tablet	7636.17 (2165.83)	0	1	53.17 (18.17)	42.63 (9.90)
p-value	0.026*	–	–	<0.001*	0.249
b-value	−0.099	–	–	11.853	−2.960
ZIGZAG LINES					
Preschool					
Paper	11609.78 (3801.26)	393.22 (1007.98)	1.68 (1.66)	34.13 (15.01)	67.46 (27.90)
Tablet	9993.20 (2860.59)	46.78 (184.47)	1.07 (0.26)	48.89 (17.22)	52.20 (16.32)
p-value	0.025*	0.105	0.056	<0.001*	0.005*
b-value	−0.122	−1.337	−0.696	14.413	−13.913
Second grade					
Paper	10986.82 (4088.58)	85.69 (174.71)	1.18 (0.49)	33.37 (14.80)	60.47 (25.23)
Tablet	9818.04 (2784.52)	232.79 (306.19)	1.31 (0.60)	47.81 (19.03)	51.09 (14.44)
p−value	0.039*	0.212	0.558	<0.001*	0.015*
b−value	−0.104	0.995	0.083	14.745	−9.917
Adults					
Paper	7938.73 (2511.17)	0	1	40.54 (15.37)	42.52 (12.70)
Tablet	7552.21 (2467.75)	0	1	51.83 (18.95)	40.50 (10.45)

(Continued)

TABLE 2 | Continued

	Writing duration (ms)	In air time (ms)	Number of pen lifts	Velocity (mm/s)	NIVs
p-value	0.188	–	–	<0.001*	0.211
b-value	−0.063	–	–	12.636	−2.348
STAIRCASE PATTERN					
Preschool					
Paper	12785.67 (4419.22)	264.90 (894.64)	1.43 (1.40)	16.84 (6.37)	76.64 (29.77)
Tablet	14368.05 (6587.95)	357.93 (1171.46)	1.36 (0.91)	20.29 (8.83)	78.88 (29.73)
p-value	0.263	0.816	0.509	0.114	0.789
b-value	0.094	0.180	−0.250	2.870	1.896
Second grade					
Paper	12917.60 (4562.05)	142.18 (373.93)	1.20 (0.40)	13.55 (5.45)	78.86 (29.11)
Tablet	11619.42 (3897.41)	323.88 (608.87)	1.46 (0.81)	18.62 (7.33)	70.20 (24.67)
p-value	0.200	0.056	0.033*	<0.001*	0.214
b-value	−0.085	1.553	0.352	4.715	−6.926
Adults					
Paper	8301.65 (2647.80)	48.86 (288.61)	1.10 (0.57)	20.76 (8.14)	48.88 (18.13)
Tablet	7663.69 (2462.25)	0	1	26.78 (10.32)	44.43 (15.60)
p-value	0.051	–	–	<0.001*	0.047*
b-value	−0.090	–	–	6.610	−5.484

The p-value refers to the comparison for Medium (tablet vs. paper). The b-value refers to the regression coefficient of the tablet condition in comparison to paper. The asterisk indicates significant effects below an alpha-level of 0.05.

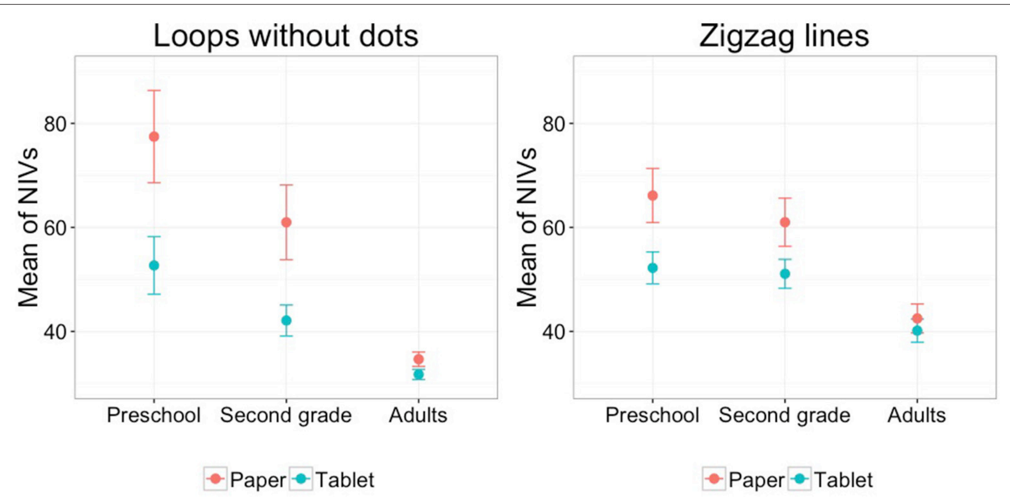

FIGURE 5 | The significant interaction between medium and group for the NIVs of loops without dots and zigzag lines (with standard errors).

The correlation analyses between writing velocity and NIVs confirmed again that these two measures are negatively related for both groups (all $p < 0.001$; second grade $\tau = -0.36$, adults $\tau = -0.20$), showing that a faster velocity is associated with fewer NIVs.

Regarding group differences we found that second graders wrote longer ($p < 0.001$, $b = 1.125$), produced longer in air times ($p < 0.001$, $b = 0.613$), and more pen lifts ($p < 0.001$, $b = -3.474$), wrote slower ($p < 0.001$, $b = -16.132$), and exhibited more NIVs ($p < 0.001$, $b = 62.577$) than adults. There were no significant interactions between the factors Medium and Group.

A quite paradoxical result that we pursued further with additional analyses was the fact that participants showed a longer writing duration and a higher writing velocity on the tablet compared to paper. This result turned out to reflect a difference in letter size between the two writing surfaces. Paired *t*-tests revealed that participants in both groups wrote larger on the tablet (second grade *M*: 1.72 cm, *SD*: 0.38 cm; adults *M*: 1.47 cm, *SD*: 0.29 cm) compared to paper (second grade *M*: 1.36 cm,

TABLE 3 | Means and standard deviations in parentheses for writing measures of the visuomotor abilities.

	Writing duration (ms)	In air time (ms)	Number of pen lifts	Velocity (mm/s)	NIVs
VISUAL MOTOR INTEGRATION (VMI)					
Preschool					
Paper	1728.87 (1210.87)	119.44 (244.08)	1.31 (0.54)	33.85 (19.08)	11.81 (7.98)
Tablet	1596.60 (1190.47)	172.12 (420.25)	1.31 (0.57)	42.86 (26.10)	10.11 (7.20)
p-value	0.157	0.960	1	<0.001*	0.030*
b-value	−0.095	0.014	0.000	9.008	−1.702
Second grade					
Paper	1935.90 (1380.33)	120.38 (243.92)	1.27 (0.48)	31.06 (21.60)	12.78 (9.51)
Tablet	1706.09 (1302.76)	161.63 (322.23)	1.31 (0.56)	42.02 (27.26)	10.83 (8.22)
p-value	0.099	0.564	0.409	0.002*	0.061
b-value	−0.140	0.153	0.042	6.976	−1.939
Adults					
Paper	1830.15 (1243.23)	219.59 (400.72)	1.45 (0.80)	29.88 (19.19)	11.79 (7.80)
Tablet	1792.31 (1300.92)	200.85 (359.22)	1.35 (0.62)	37.04 (23.89)	10.51 (7.78)
p-value	0.562	0.586	0.104	<0.001*	0.107
b-value	−0.033	−0.160	−0.115	6.976	−1.135
MOTOR COORDINATION (MC)					
Preschool					
Paper	3971.81 (2179.46)	394.59 (688.39)	1.50 (0.79)	15.04 (7.13)	27.87 (16.39)
Tablet	3819.11 (2416.13)	376.71 (778.39)	1.44 (0.78)	18.71 (8.69)	25.13 (16.19)
p-value	0.222	0.291	0.520	<0.001*	0.105
b-value	−0.076	−0.351	−0.051	3.674	−2.742
Second grade					
Paper	3995.59 (2470.78)	312.07 (530.39)	1.48 (0.75)	15.17 (7.40)	27.86 (17.27)
Tablet	4040.81 (2462.22)	308.78 (558.84)	1.42 (0.70)	17.19 (7.96)	25.85 (15.69)
p-value	0.866	0.572	0.388	0.037*	0.200
b-value	0.010	−0.175	−0.061	1.947	−2.014
Adults					
Paper	2582.54 (1546.54)	199.66 (380.76)	1.40 (0.73)	21.53 (11.40)	16.77 (9.98)
Tablet	2938.22 (1694.12)	232.25 (429.96)	1.41 (0.71)	21.00 (10.29)	17.02 (10.55)
p-value	0.028*	0.682	0.946	0.964	0.969
b-value	0.127	0.119	−0.005	−0.044	−0.038

The p-value refers to the comparison for Medium (tablet vs. paper). The b-value refers to the regression coefficient of the tablet condition in comparison to paper. The asterisk indicates significant effects below an alpha-level of 0.05.

SD: 0.33 $t_{(296)} = -18.24$, $p < 0.001$; adults *M*: 1.20 cm, *SD*: 0.32 cm; $t_{(299)} = -18.20$, $p < 0.001$).

We conducted another additional analysis to test if our participants adapted to the unfamiliar and smoother surface of the tablet over time. Therefore, we ran linear mixed-effects models with the NIVs as the dependent variable and item number in increasing order as the independent variable. If participants adapted to the unfamiliar writing surface then the NIVs should decrease over the course of task (writing the phrase 10 times), revealing an increase in automatization and a decrease in the focus on the graphomotor execution of the task. For both media (tablet and paper) the NIVs significantly decreased for both groups (second grade: paper: $p < 0.001$, $b = -1.969$, tablet: $p < 0.001$, $b = -1.982$; adults: paper: $p < 0.001$, $b = -0.720$, tablet: $p < 0.001$, $b = -0.772$) from the first (second grade: paper: *M*: 132.68, *SD*: 22.73; tablet: *M*: 130.95, *SD*: 20.15; adults: paper: *M*: 59.61 *SD*: 17.43; tablet: *M*: 64.26 *SD*: 14.85) to the last item (second grade: paper: *M*: 109.00, *SD*: 12.76; tablet: *M*: 117.73, *SD*: 15.84; adults: paper: *M*: 50.56 *SD*: 14.09; tablet: *M*: 54.08 *SD*: 16.00) of writing repetitively the same phrase. **Figure 6** visualizes the decrease in NIVs for both groups and both media.

DISCUSSION

The present study investigated whether the writing surface (tablet vs. paper) influences the product and the process of writing. In order to identify task-dependent modulations of this influence,

TABLE 4 | Means and standard deviations in parentheses for writing measures of writing the phrase "sun and waves."

	Writing duration (ms)	In air time (ms)	Number of pen lifts	Velocity (mm/s)	NIVs
WRITING "SUN AND WAVES"					
Second grade					
Paper	14753.40 (3446.42)	2664.79 (1232.79)	5.26 (1.33)	14.16 (4.91)	117.24 (17.27)
Tablet	17068.82 (4003.57)	3076.98 (1518.31)	5.38 (1.46)	17.11 (5.21)	119.45 (15.69)
p-value	<0.001*	0.106	0.711	<0.001*	0.334
b-value	0.144	0.109	0.075	3.003	2.101
Adults					
Paper	5039.54 (1414.62)	1550.43 (642.99)	8.83 (3.31)	30.46 (7.90)	56.45 (15.63)
Tablet	5872.78 (1823.93)	1741.86 (617.29)	8.51 (3.25)	35.88 (8.93)	59.68 (15.67)
p-value	<0.001*	0.002*	0.031*	<0.001*	0.010*
b-value	0.156	0.104	−0.369	6.502	2.982

The p-value refers to the comparison for Medium (tablet vs. paper). The b-value refers to the regression coefficient of the tablet condition in comparison to paper. The asterisk indicates significant effects below an alpha-level of 0.05.

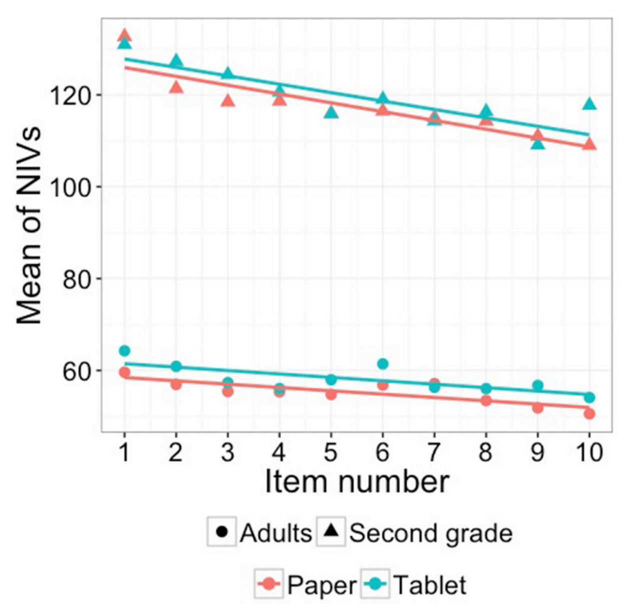

FIGURE 6 | The mean of the NIVs for each item of "sun and waves" on paper and on the tablet computer (with 95% confidence intervals).

we used three tasks to test (1) graphomotor abilities using repetitive patterns, (2) visuomotor abilities, and (3) handwriting abilities. As a second aim we sought to reveal the relationship between the evaluation of handwriting quality and the dynamics of the handwriting process. Thirdly, we wanted to investigate the different levels of handwriting automaticity in three groups (preschoolers, second graders, and adults).

Our results demonstrate important differences between writing on a tablet and writing on paper. Similar to the study by Gerth et al. (2016) the findings are task-dependent and specific to the writing demands of the tasks. We will interpret our results in more detail according to the comparison between writing surfaces (Section Handwriting on the Tablet vs. Paper), the comparison between quality measures and process measures of handwriting (Section Handwriting Product vs. Process) and between-group differences (Section Age-Related Effects of Handwriting Performance).

Handwriting on the Tablet vs. Paper

Our evaluation of handwriting quality yielded differences between writing on the tablet and on paper for the three groups. In particular the children groups showed a higher handwriting quality when writing on paper for some of the graphomotor and for both visuomotor tasks. Contrastingly, the adults showed the opposite pattern (better handwriting quality when writing on the tablet) for two of the graphomotor tasks (zigzag lines and staircase pattern). Since children are not automatized in their writing movements, they seem to be challenged most by a decrease in proprioceptive feedback of the writing surface. The adults, however, seem to adapt to the smoother surface quite quickly and effortlessly during the course of the task because they show the better performance on the tablet for the last two tasks in this task battery (zigzag lines and staircase pattern). We can only speculate that adults might have concentrated less on the accurate execution of the task on paper because this writing surface is very familiar to them.

Regarding the handwriting process measures we found a faster writing velocity on the tablet compared to paper for all groups and the majority of tasks. These findings indicate that the pen was sliding faster on the tablet which might have been due to the lower friction of the surface. In order to perform a fluent and regular writing movement, participants had to adapt their graphomotor execution. In our first task—testing graphomotor abilities by copying repetitive pattern—we found significantly faster writing velocity for all tasks and all groups (except for the staircase pattern in the preschoolers). When comparing the results between media for the visuomotor tasks—VMI and MC—we found again that all groups performed the tasks with a higher velocity on the tablet compared to paper (except for the MC in the adults' group). The additional analyses comparing task demands revealed main differences for all writing measures in the children's groups and three handwriting measures for the adults (writing duration, velocity, and NIVs). Apparently the task demands of the MC were higher compared to the VMI because participants had to stay in a predefined writing area. Drawing the attention to the writing process clearly hampers the automaticity of the writing movements and leads to a slower execution (Tucha and Lange, 2005; Tucha et al., 2008). In our third task—probing handwriting—participants copied a phrase of three words for ten times. This task directly tests automatized handwriting movements that are stored in motor programs of experienced writers. We obtained a longer writing duration and a faster writing velocity for both groups on the tablet which is due to the fact that both groups wrote bigger letters on the tablet with a higher velocity. The smoother surface presumably requires a higher graphomotor control to counter the lower proprioceptive feedback of the surface (lower friction). One way to adapt the writing movements is to enlarge the letter size which corroborates findings of previous research (Denier van der Gon and Thuring, 1965; Alamargot and Morin, 2015; Gerth et al., 2016). It is interesting to see that even second graders who are in the middle of handwriting acquisition are already capable of compensating the smoother surface with this adaptation in graphomotor execution. This might reveal that they are relying more on the proprioceptive rather than visual feedback similar to experienced writers, which might reflect that they use the ability of motor anticipation for writing and activate their motor programs quickly and automatically (Kandel and Perret, 2015).

Handwriting Product vs. Process

In our study we used two measures for the handwriting assessment—the handwriting quality evaluated by a visual score and the handwriting process measures as a direct measure of the level of automaticity in handwriting. As expected, both measures reflect different dimensions of handwriting task results (similar to results by Fliesser et al., in preparation). The score for the handwriting quality relates to the visual legibility and alignment of words and may be appropriate to test the level of handwriting proficiency of the writer since children are taught to write neatly and copy the given letter as accurately as possible from the teacher or from a book. Our findings show that all groups were able to copy repetitive patterns, geometric forms, and words on both media. The disadvantages of performing the tasks on the tablet are expected since the smoother surface introduces an unfamiliar writing surface with a lower friction that has to be countered with higher graphomotor control of the writing movements. This is also visible in the higher writing velocity (as one of our handwriting process measures) for nearly all our tasks in all groups on the tablet. The velocity, which is negatively related to the NIVs as measure of an automatized and fluent handwriting movement, reflects the participant's ability to coordinate fine muscles to control the graphomotor execution and produce a fluent movement. Hence these process measures seem to refer to the motor component of writing rather than the visual control. Therefore, we believe that only the combination of both measures provides a complete picture of the level of handwriting skills in children and adults: product-oriented handwriting measures reflect the visual control and feedback during writing, whereas process-oriented measures mirror a combination of the graphomotor and visual control.

Age-Related Effects of Handwriting Performance

When comparing the handwriting performance of our three groups—preschoolers, second graders, and adults—we obtained results in the predicted direction for the handwriting quality and the handwriting process measures. The preschoolers who have not received any writing instructions yet produced the lowest handwriting quality, wrote longer, and slower than the other two groups, paused for a longer time, lifted the pen more often and produced more NIVs in all tasks. Since we designed our tasks in such a way that they were suited for preschoolers they could perform them even without proper writing instructions. Nevertheless, their graphomotor execution was clearly at a non-automatized level and particularly the high number of error points for the graphomotor abilities tasks shows that the tasks were quite demanding. In particular, preschoolers lifted the pen more often than adults in all four tasks and they lifted the pen more often than second graders for loops without dots and zigzag lines. Especially zigzag lines who denote diagonal lines are very demanding for preschool children (Lange-Küttner, 1998) and our results seem to indicate that they used more visual control than second graders and adults to correctly copy the zigzag pattern (=longer pauses and more pen lifts). This behavior might suggest a motor anticipation of the upcoming stroke which takes longer for a complex and unfamiliar graphomotor movement (Kandel and Perret, 2014).

Regarding our visuomotor tasks we found that the preschoolers and second graders wrote faster but produced more NIVs than the adults for the MC. When combining these results with the scores of the handwriting quality evaluation we interpret this finding as a speed-accuracy trade-off. Both children groups obtained a lower accuracy score than adults in this task, but they executed the task faster. Hence, our findings indicate that the MC was more demanding for the children. They performed faster (higher velocity), but had to focus their attention stronger on the graphomotor execution (higher NIVs) and were still less accurate. This result is unsurprising since the MC required the participants to stay in a predefined writing space to copy the geometrical forms accurately. Apparently the children had greater difficulties to control the pen on the smoother tablet surface during this task. The combination of visual and graphomotor control without familiar proprioceptive feedback hampered the (automaticity in) writing movements which is similar to studies during which participants had to visually track the pen tip during writing and produced more NIVs (Marquardt et al., 1996; Tucha and Lange, 2005; Tucha et al., 2008; Gerth et al., 2016).

Our handwriting task revealed that the second graders wrote slower, lifted the pen more often, made longer pauses and exhibited more NIVs compared to the adults. Further, both groups compensated the smoother surface of the tablet with an increase in letter size which corroborates findings in previous research (Denier van der Gon and Thuring, 1965; Alamargot and Morin, 2015; Gerth et al., 2016). Our additional analysis testing for a change in the NIVs over all ten items of writing the phrase "Sonne und Wellen" showed that for both groups the NIVs decreased from the first to the last item. Since this task directly depicts handwriting performance it might have been easier for both groups compared to the other two tasks, during which they had to copy patterns, because they write words probably every day. Therefore, we interpret the declining NIVs as a decrease in attention to the writing process and an adaptation of the handwriting movements to the writing surface (even to the smoother tablet).

Apart from main group differences we also found significant interactions between the factors Medium and Group. For the handwriting product evaluation we see a difference in the performance between the adults and the children groups for the zigzag lines and the staircase pattern (see **Figure 4**). The children produced more error points on the tablet whereas the adults performed worse on paper. When looking more closely at the different categories of the error points we saw that the worse performance of the adults is due to the penalty for lifting the pen while drawing the pattern. Adults lifted the pen more often on paper compared to on the tablet. This suggests that they probably resisted the urge to lift the pen on the tablet presumably because they did not want to risk not to be able to start the new stroke at exactly the same point where they ended the last stroke. For the tablet there was a small gap between the plastic writing surface and the actual screen with the visual feedback of the pen tip. When performing the task on paper there is no gap between the pen tip and the surface, therefore the end point of the previous stroke could be targeted more easily.

The majority of significant interactions between medium and group is due to the fact that the preschoolers show a significant difference between performing the tasks on paper or on the tablet whereas the adults do not show a between-media difference. This result can be interpreted in the light of a difference in experience with the two media. Adults might be more familiar with tablets in general than preschoolers, although this experience could be mostly related to typing on the tablets rather than writing with a pen on the tablet. The lower experience with the tablet as a writing surface is also visible in our data in a higher variability (greater standard deviations) in handwriting performance on the tablet compared to paper. However, all our participants show this higher variance. Therefore, we think that the interactions between media and group in our results rather stem from a different degree in handwriting automaticity of our groups. Especially preschoolers show differences between the two media because they are not automatized in their writing movements and have to counter the low friction of the tablet surface with additional focus on their graphomotor execution. The adults, however, adapt very quickly to the smoother tablet surface because their handwriting movements are stored in the motor programs and they simply need to fine-tune them to counter the lower friction. Apparently this is very difficult for beginning learners. The second graders are somewhere in the middle of their handwriting development. This is also reflected in our results. The second graders show media-differences in the handwriting process measures for the demanding tasks similarly to the preschoolers (e.g., zigzag lines, staircase pattern), but they mostly pattern with the adults' group regarding their handwriting performance.

CONCLUSION

The findings of our study provide a first answer to the question whether there are age-related effects in graphomotor execution due to differences in writing surfaces. We found differences between writing on paper compared to the tablet. These differences were partly task-dependent. Generally, we found a higher writing velocity for writing movements on the tablet which indicates that all groups—even the experienced writers—were influenced by the lower friction of the writing surface. Apparently the pen was sliding stronger on the smoother surface of the tablet.

Our results of the between-group analyses revealed that the non-writers (preschoolers), beginning writers (second graders), and the experienced writers (adults) were differently influenced by the two writing surfaces. Especially when the task required a combination of visual and graphomotor control (such as the MC) the children were particularly challenged by the smoother surface of the tablet. Therefore, we doubt that it is recommendable to use tablets in schools for writing acquisition because the smoother surface represents an additional challenge for learners of writing that they have to counter with an increased control of their graphomotor execution. This might lead to a prolongation of handwriting acquisition and possibly increases children's frustration when trying to write most legibly.

Further we do not think that it is wise to simply digitize paper-pencil-versions of a test to obtain measures of the handwriting dynamics. Our results show a task-dependency and differences in task-demands that might lead to unexpected results due to the unfamiliar and smoother surface of a tablet and not due the experimental manipulation itself.

AUTHOR CONTRIBUTIONS

TD has been part of the Research Group, and is currently at the University of Regensburg. Author contributions are as follows: substantial contributions to the conception and design of the project (all authors); data acquisition (SG), data analysis (SG), and interpretation of data (SG, JF, AK, TD, MF), drafting the manuscript (SG, JF), revising it critically for important intellectual content (all authors).

FUNDING

This research was funded by the Land Brandenburg, Germany. We acknowledge the support of the Deutsche Forschungsgemeinschaft and Open Access Publishing Fund of University of Potsdam.

ACKNOWLEDGMENTS

We thank the children and the students at the University of Potsdam who participated in our study. Further we are grateful to Elisabeth Fleischhauer, Sophia Czapka, Tim Linka, and David Ziegert for their help with the data collection, Jessica Grasso, Eliah Aila Wolff, Gerit Brenner, and Maria Windolff for their support with the data preprocessing and the members of the Research Group: Diversity and Inclusion, University of Potsdam for helpful comments and suggestions.

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Conflict of Interest Statement: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

frontiers in Psychology

ORIGINAL RESEARCH
published: 30 August 2016
doi: 10.3389/fpsyg.2016.01264

The Role of Interactional Quality in Learning from Touch Screens during Infancy: Context Matters

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Interactional quality has been shown to enhance learning during book reading and play, but has not been examined during touch screen use. Learning to apply knowledge from a touch screen is complex for infants because it involves transfer of learning between a two-dimensional (2D) screen and three-dimensional (3D) object in the physical world. This study uses a touch screen procedure to examine interactional quality measured via maternal structuring, diversity of maternal language, and dyadic emotional responsiveness and infant outcomes during a transfer of learning task. Fifty 15-month-old infants and their mothers participated in this semi-naturalistic teaching task. Mothers were given a 3D object, and a static image of the object presented on a touch screen. Mothers had 5 min to teach their infant that a button on the real toy works in the same way as a virtual button on the touch screen (or vice versa). Overall, 64% of infants learned how to make the button work, transferring learning from the touch screen to the 3D object or vice versa. Infants were just as successful in the 3D to 2D transfer direction as they were in the 2D to 3D transfer direction. A cluster analysis based on emotional responsiveness, the proportion of diverse maternal verbal input, and amount of maternal structuring resulted in two levels of interactional quality: high quality and moderate quality. A logistic regression revealed the level of interactional quality predicted infant transfer. Infants were 19 times more likely to succeed and transfer learning between the touch screen and real object if they were in a high interactional quality dyad, even after controlling for infant activity levels. The present findings suggest that interactional quality between mother and infant plays an important role in making touch screens effective teaching tools for infants' learning.

Keywords: transfer of learning, touch screens, interactional quality, maternal scaffolding, teaching tool, infant, elaborative parenting style, emotional responsiveness

OPEN ACCESS

Edited by:
Jordy Kaufman,
Swinburne University of Technology, Australia

Reviewed by:
Michelle Neumann,
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Specialty section:
This article was submitted to Developmental Psychology, a section of the journal Frontiers in Psychology

Received: *18 May 2016*
Accepted: *09 August 2016*
Published: *30 August 2016*

Citation:
Zack E and Barr R (2016) The Role of Interactional Quality in Learning from Touch Screens during Infancy: Context Matters. Front. Psychol. 7:1264. doi: 10.3389/fpsyg.2016.01264

INTRODUCTION

The launch of the iPad in April 2010 was followed by a rapid and unregulated release of more than 80,000 tablet applications or "apps" tagged as educational in the App Store (Apple, 2016). These inexpensive and accessible programs can easily be downloaded onto touch screen enabled phones and tablets. As such, use of touch screens during early childhood is increasing at a rapid pace (Radesky et al., 2015).

The American Academy of Pediatrics (2013) recommends that parents co-use educational media with their children in limited quantities. Co-using media together allows parents to bridge the gaps in their child's knowledge of the media content and use of the media device. Parents have not consistently adopted these recommendations and these policies have not yet fully considered use of newer tablet touch screen-based technologies (Neumann, 2015). Parents report co-using more often with their children while watching television compared to using smartphones or tablets (Rideout, 2013; Connell et al., 2015). Parents, teachers, and app developers need more evidence-based information about how to best support children's learning from touch screen devices (Lerner and Barr, 2014; Hirsh-Pasek et al., 2015; Barr and Linebarger, 2016; Troseth et al., 2016).

There is a small but growing body of literature on learning from tablets and touch screens during early childhood (see Barr, 2013; Troseth et al., 2016). On the one hand, the inherent interactivity of touch screens may facilitate learning, such that learning may be less dependent on parental support. For example, toddlers who have contingent interactions with touch screens transfer learning in an object retrieval task (Choi and Kirkorian, 2016) and learn more words than children who view a non-interactive video (Kirkorian et al., 2016). On the other hand, children may appear to be proficient in their interactions with the device, but this may not allow for them to transfer information beyond the app (Moser et al., 2015; Neumann and Neumann, 2015). Interactive media contexts are increasingly becoming part of the day-to-day environments of infants and their caregivers. It is important to understand whether, and in what ways parent–child interactions may enrich these experiences. We do know a considerable amount about the context of learning with real objects.

Social interaction with parents and other significant adults help to shape the course of cognitive development during infancy and childhood (e.g., Bandura, 1977, 1986; Vygotsky, 1978; Rogoff, 1990; Farrant and Reese, 2000). Children have a zone of proximal development, that is, the difference between what they are able to accomplish independently and what they can achieve with the help of a more experienced adult (Vygotsky, 1978). High interactional quality between infants and caregivers should provide a scaffold under challenging learning conditions (Wood et al., 1976). High quality parent–child interactions are characterized by parents' use of appropriate amounts and types of verbal input, emotional responsiveness where parents are sensitive to the developmental needs of the child and the child is engaged, and parents who provide structure and guidance during everyday activities and teaching tasks (DeLoache and DeMendoza, 1987; Rogoff, 1990; Farrant and Reese, 2000; Dodici et al., 2003). The present study examines whether dyadic interactional quality—characterized in this way—is associated with learning from a novel touch screen tool during infancy.

Much of the research in this domain has focused on maternal behavior during parent–child interactions. Mothers' sensitive and contingent verbal input during dyadic interactions shapes their infant's immediate phonological patterns (Goldstein and Schwade, 2008) and vocal development over time (Gros-Louis et al., 2014). Other research shows that mothers differ in how they talk about the past with their children, with some mothers being classified as elaborative and others as repetitive (e.g., Reese and Fivush, 1993). More elaborative maternal scaffolding during infancy predicts higher and more diverse productive vocabulary outcomes for infants and preschoolers (Hart and Risley, 1995; Haden et al., 1996; Hoff, 2003; Britto et al., 2006) and increased child engagement and responsiveness to verbal requests (Hudson, 1990). Mothers adjust their verbal scaffold during book reading based on the developmental level of their child (DeLoache and DeMendoza, 1987; Sénéchal et al., 1995). These measures of maternal scaffolding are dependent upon the bidirectional relationship between the parent and child.

As technology created specifically for young children proliferates, researchers have more closely examined parent–child interactions during television viewing and computer storybook reading (Stoneman and Brody, 1982; Lauricella et al., 2009). For example, during a computer book reading task between caregivers and preschoolers, Lauricella et al. (2009) found that when the child operated the mouse, caregivers concentrated on scaffolding the mechanics of the task. Conversely, when the caregivers operated the mouse, caregivers concentrated on scaffolding children's vocabulary and comprehension of the story.

Variation in interactional quality has also been found in studies of co-viewing during infant-directed programming (Barr et al., 2008; Fender et al., 2010; Fidler et al., 2010). In general, the more parents provided labels and descriptions and asked about the video content, the more likely infants were to vocalize (Fender et al., 2010), to look at the screen (Barr et al., 2008; Fidler et al., 2010) and to interact with the media characters (Barr et al., 2008). In a study on toddler word learning from video, Strouse and Troseth (2014) found that 24-month-olds only transferred a word they learned from watching a video to a real 3D object when a parent provided verbal scaffolding. Taken together, these results suggest that the presence of a contingent, social partner may have important influences on infants' learning from books, television, and computers.

Back-and-forth responsiveness between infants and their parents shapes infant development. Researchers often use global rating scales to measure the contingent nature of parent–infant interactions. Rather than counting the frequency of behaviors, for global scales researchers make a qualitative rating based on how often a parent or child displays specific behaviors or an interactional style (Brito et al., 2014). Although, responsiveness and maternal structuring have been indexed in a number of different ways, across a wide range of contexts, and with diverse populations (e.g., Bornstein, 1989; Martin, 1989; Barnard and Kelly, 1990; Rogoff et al., 1993; Biringen et al., 1998; Biringen, 2000), the construct consistently predicts cognitive, language, and social outcomes across populations and throughout development (Bornstein, 1989; Tamis-LeMonda et al., 2001; Laible and Song, 2006; Bornstein et al., 2008; Kaplan et al., 2009; Brito et al., 2014).

For an adult's response to be contingent, it must be sequential to, and dependent on the infant's behavior. In face-to-face interactions, contingent responses help keep and direct infants' attention. Joint attention refers to "following the direction of attention of another person to the object of their attention"

(Butterworth, 2001, p. 213). Infants' ability to jointly attend develops gradually across the first 2 years of life. Eye gaze and pointing are simple ways for mothers and infants to respond to or initiate joint attention. By the end of their first year, most infants have learned that interactions are based on reciprocal and interchangeable roles (Shaffer, 1977). However, children's responses to their mother vary significantly across individual dyads (Martin, 1989; Barnard and Kelly, 1990; Biringen et al., 1998; Biringen, 2000; Easterbrooks et al., 2005).

Contingency is also important for toddlers' language learning from screen media (Roseberry et al., 2014; Kirkorian et al., 2016). For example, toddlers learned new words from a contingent, video chat interaction as well as from a face-to-face interaction; however, they did not learn the words from a non-contingent, pre-recorded video (Roseberry et al., 2014). Research examining dyadic parent–child interactions has typically focused on parent–infant exchanges during familiar activities such as toy play, feeding time, and book reading. One area that has received less attention is parental *teaching* of infants in novel, supportive contexts.

Interactional quality during maternal teaching, indexed by verbal input, responsiveness, and contingency, is also a major construct that predicts children's performance on problem solving and puzzle tasks (Maccoby and Martin, 1983; Goldberg et al., 1989; Barnard and Kelly, 1990; Britto et al., 2006; Levine et al., 2012; Fisher et al., 2013). For example, Levine et al. (2012) examined parent–child interactions during puzzle play every 6 months beginning when children were 2 years old. At 4.5 years children completed a mental rotation task. They found that the quality of parent engagement and spatial language use during puzzle play predicted children's later performance on the mental rotation task.

In general, research examining the role of interactional quality on child learning outcomes has largely relied on older age groups or familiar tasks (e.g., Laosa, 1980; Britto et al., 2006; Fisher et al., 2013); but caregiver teaching has also been examined in infants (Dixon et al., 1984; Brachfeld-Child, 1986; Banerjee and Tamis-LeMonda, 2007). For example, Brachfeld-Child (1986) found that parents use a variety of teaching strategies when asked to teach their 8-month-olds a new skill – putting a cube in a cup – including attention-getting behaviors and pointing, making the test object more accessible and stable, and vocalizing. This research has primarily focused on providing broad descriptions of maternal behavior and child behavior (e.g., persistence) without connecting the teaching to *immediate* infant success on a task (e.g., Britto et al., 2006; Banerjee and Tamis-LeMonda, 2007). Even when immediate success has been measured (e.g., Laosa, 1980), the success rate has been low, suggesting that the task may not have been developmentally appropriate for the age group tested. Finally, both maternal modeling and verbal instruction of the learning outcome are often permitted during the teaching task (e.g., Dixon et al., 1984; Brachfeld-Child, 1986) making it impossible to disentangle children's ability to complete the task in the presence or absence of explicit modeling.

In order to examine the role of interactional quality on infant learning, a task needs to be devised with two criteria in mind: (1) the infant needs to be able to physically engage in the task and (2) it should be a task in which infants have demonstrated a difficulty in completing on their own. Transfer of learning between 2D and 3D tasks meet these criteria.

Learning to apply knowledge from a touch screen is complex because it involves transfer of learning. Researchers have demonstrated that infants show a "transfer deficit" (Barr, 2010), that is, they have difficulty transferring learning from 2D sources such as books, television, and touch screens to real-world, 3D objects in comparison to learning from live, face-to-face interactions with real objects (e.g., Barr and Hayne, 1999; Anderson and Pempek, 2005; Zack et al., 2009). For example, Zack et al. (2009) used a novel touch screen to examine whether infants would imitate actions modeled on a touch screen device. The experimenter pushed a button either on a touch screen or a real toy to produce an interesting sound (e.g., a honking sound). Using the touch screen device allowed the researchers to examine how flexible infants could be in transferring learning from the touch screen device to the real toy and vice versa. For the 3D/2D condition, an experimenter pushed a button on the 3D toy and infants were given the opportunity to imitate the action on a 2D touch screen image of the toy. Infants saw the reverse for the 2D/3D condition. Infants in baseline only conditions did not view a demonstration before being shown the test 3D toy or 2D touch screen image.

Zack et al. (2009) reported three major findings with their novel touch screen task. First the task has a low baseline for both the 2D touch screen test and 3D object test, a quintessential hallmark for an experimental imitation task (e.g., Barr and Hayne, 2000). Second, infants performed above baseline in all experimental conditions. Finally, although infants performed significantly above baseline, indicating that they could transfer learning between the touch screen and the real toy, they learned significantly less compared to when the demonstration and test both occurred on the touch screen (2D/2D) or on the real toy (3D/3D). In a follow-up study, Zack et al. (2013) found that language cues did not augment infant imitation scores to above original transfer performance on the touch screen transfer task. The touch screen transfer task therefore meets the two criteria: infants could physically engage in the task but the transfer task was sufficiently challenging.

In the present study, we therefore used the touch screen task to explore whether interactional quality predicts infant learning. Mothers were asked to teach the touch screen transfer of learning task to their infants. The touch screen transfer conditions (Zack et al., 2009) were adapted into a semi-naturalistic teaching task. Mothers were given a 3D toy, and a static image of the object presented on a touch screen. Mothers had 5 min to teach their infant that a button on the real toy worked in the same way as a virtual button on the touch screen image (or vice versa). The goal of this study was to examine whether variations in interactional quality between mother and infant predict infants' ability to transfer learning between 2D and 3D. We predicted that higher interactional quality within the dyad—indexed via verbal input, responsiveness, and structuring—would be associated with greater infant success on the touch screen transfer task.

MATERIALS AND METHODS

Participants

Participants were fifty 15- to 16-month-old (25 males) full-term healthy infants and their mothers. They were recruited through commercially available records, childcare centers, and by word of mouth. Mother–infant dyads were visited in their homes between January, 2008 and December, 2009. Infants ranged in age from 15 months and 1 day to 16 months and 18 days (M = 15 months, 16 days, SD = 11.0 days). Participants were Caucasian (n = 39), Latino (n = 3), Asian (n = 3), and of mixed race (n = 5). The majority of infants were from middle- to upper-class families [rank of socioeconomic status (SEI) using Nakao and Treas (1992) calculation, M = 79.7, SD = 12.2]. Families were well-educated (parent education M = 17.84 years, SD = 0.5).

Mother–infant dyads were randomly assigned to one of two conditions: *3D demo object/2D test image* (3D/2D) or *2D demo image/3D test object* (2D/3D). There were 25 mother–infant dyads per condition. The primary language spoken at home and during the task was English for 96% of the sample (n = 48). Two mothers spoke in English and Spanish during the teaching task, as this was typical of an interaction in their home. An additional five mother–infant dyads were excluded from the final sample due to equipment failure (n = 1), maternal failure to follow study directions (n = 2), infant fussiness (n = 1) and an inability to transcribe the session (n = 1).

Apparatus

We created a bus and a cow stimulus from non-commercially available button boxes (Zack et al., 2009, 2013) (**Figure 1**). Mothers were randomly assigned to either the bus or cow stimulus for use in teaching the transfer task.

3D Stimuli

Two button boxes (16.5 wide × 15 tall × 5.5 cm deep) were decorated to create a school bus and a cow. The bus has a slightly recessed rectangle-shaped button (2.2 cm × 3 cm) on the right surface in the middle of the box. Pressing the button produced a horn honking sound. The cow has a slightly recessed circular button (2.2 cm × 2.2 cm in diameter) on the left surface in the middle of the box. Pressing the button produced a cow mooing sound.

2D Stimuli and Touch Screen

Digital photos were taken of the bus and cow 3D button boxes and depicted on a 17 inch LCD touch screen. The button areas were programmed such that pressing the virtual button on the touch screen produced the same sound as pressing the actual button on the 3D toy. The images were equated in size to the 3D object at approximately the same viewing distance.

Experimental Set-Up

Two lap tables (each 61 wide × 32 tall × 37.5 cm deep) were placed side-by-side on the floor. The 3D object was placed on one table and the touch screen on the second table (**Figure 1**). Mothers and their infants sat on the floor at the lap tables, facing the 2D touch screen and 3D object. The 3D object and touch screen were covered with a black cloth until the start of the session.

Procedure

This study was carried out in accordance with the recommendations of the Georgetown University Institutional Review Board with written informed consent from mothers of all subjects. Mothers of all subjects gave written informed consent in accordance with the Declaration of Helsinki. After obtaining informed consent, an experimenter described the study and gave mothers written and verbal instructions. The

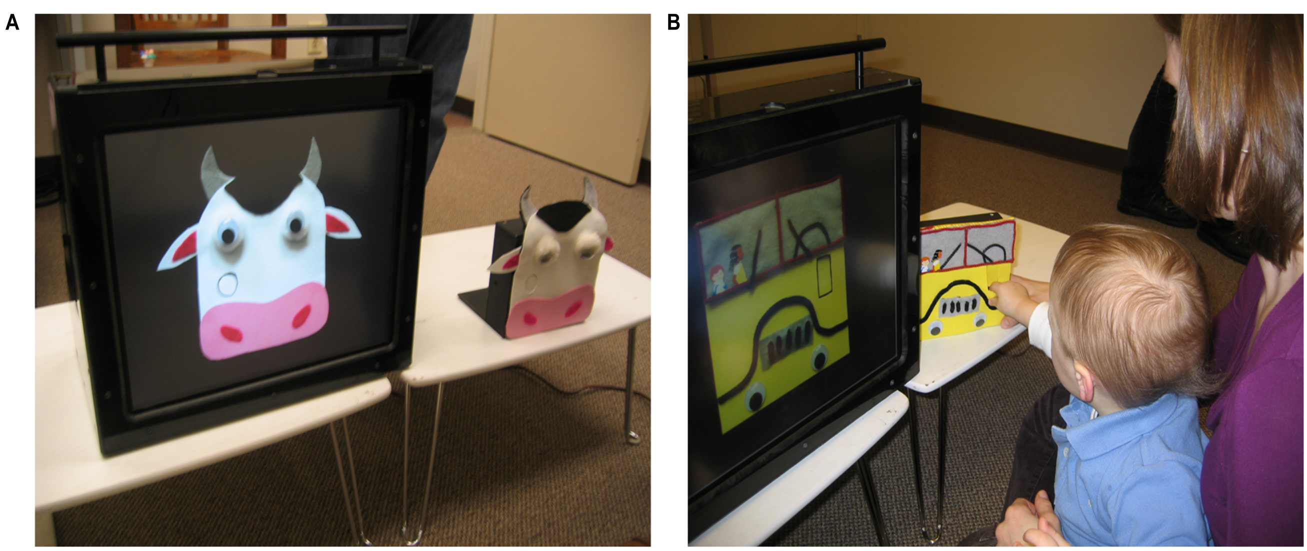

FIGURE 1 | (A) 2D touch screen and 3D object experimental stimuli. **(B)** Set-up for the touch screen teaching task.

instructions included a description and illustration of the task set-up, goals, and restrictions. We instructed mothers to teach their infant about the relationship between the 3D object and 2D touch screen image. That is, that a button on the real object works in the same way as a virtual button on a touch screen (or vice versa). For example, a mother assigned to the 2D/3D condition was allowed to interact with or discuss either the 3D object or touch screen. But mothers had one caveat. They could not directly point out the 3D button, push the 3D button, or say push with regard to the 3D object. The mother's goal was for her infant to figure out the connection between the 2D touch screen and the 3D object. The mother succeeded if her infant pressed the 3D button within the 5-min session.

One experimenter videotaped the session from behind the two lap tables. The mother's and infant's face were visible at all times. A second experimenter videotaped the session from behind the mother–infant dyad. The mother's and infant's arms and the touch screen and object were visible at all times. The session ended when the infant pressed the button on the 3D object (2D/3D condition) or 2D touch screen image (3D/2D condition), or at 5 min, whichever came first.

Questionnaires

MacArthur Communicative Development Inventory (CDI, Level 1)

Infant short form is an 89-word parent report checklist of words their infant understands and understands and says (Fenson et al., 2000). Percentile rank was determined by the age and gender of the infant for language comprehension and production. Infants' language ability was within expected norms for 15- to 16-month-olds ($M = 40.9$, $SD = 32.5$).

Household and Infant Screen Media Use

Mothers were asked to estimate their daily household screen media use and amount of time their infant was exposed to television on a typical day. Touch screen use was not included in the questionnaire because very few homes had touch screen phones or tablets at the time data was collected.

Coding – Task Variables

Transfer Success

A primary coder scored from videotape whether infants performed the target action (pressing the button) on the test object (2D/3D condition) or test image (3D/2D condition). Transfer score was '0' if the infant did not press the button within 5 min from the start of the session. The transfer score was '1' if the infant did press the button. A secondary coder scored 50% of the sessions; inter-observer reliability was 100%.

Latency to Success

Latency to success was calculated from infant's first touch of the test stimulus to be consistent with previous experimental studies using touch screens (Zack et al., 2009, 2013). Infants who did not successfully transfer on the task received a latency time of 5 min, the maximum amount of time dyads had to complete the task.

Coding – Maternal Scaffolding

Proportion of Diverse Verbal Input

The transcripts were coded to examine how much "new" information the mother provided during the task. An utterance was coded as *diverse* in the transcript if the mother had not provided the same information within the previous 10 utterances. An utterance was defined as *repetitive* if the mother had provided the same content (Reese and Fivush, 1993) within the previous 10 utterances (see **Table 1**). A Pearson product-moment correlation yielded an inter-observer reliability coefficient of 0.96 based on 30% of the sessions.

Maternal Modeling

A coder scored each time the mother pushed the button on the demonstration stimulus; the rules of the task stipulated that mothers were not permitted to push the button on the test stimulus. A "button push rate" was calculated to control for differences in session length across dyads. The rate was calculated by taking the total number of times the mother pushed the button on the demonstration stimulus and dividing by the individual session length for each dyad (maximum time = 5 min). Reliability was 89% ($\kappa = 0.76$) based on 34% of the data.

Maternal Structuring

Maternal structuring was characterized by how often the mother organized her infant's attention, motivation, and involvement in the task and attempted to teach the transfer task. The dimensions were adapted from other research groups (Goldberg et al., 1989; Barnard and Kelly, 1990; Biringen, 2000). A mother was classified as either providing an *optimal* amount of structure (score = 1) or *too little/too much* (score = 0) structure. Mothers who provided an optimal amount of structure would let their infants be autonomous while also guiding their behavior to reach the goal. For example, 80% of mothers used verbal matching cues to illustrate that a feature on the 2D image was also present in the 3D object. Reliability was 93% ($\kappa = 0.84$) based on 30% of the data.

TABLE 1 | (Left) A transcript of a diverse interaction. (Right) A transcript of a repetitive interaction.

Diverse	Code	Repetitive	Code
What does a cow say?	N	Look at this	N
Moo	N	Look at that	R
And there's another cow	N	Look at that	R
Look (child's name)	N	It's a screen	N
This is how I make him go moo	N	Doesn't that look like the other toy?	N
And look – 1 cow, 2 cows	N	Doesn't it look like the other toy?	R
I know it's so funny	N	It's yellow	N
Can we make him go moo?	N	Looks like the other toy, doesn't it?	R

Each phrase is coded N for new or R for repeated content.

Coding – Infant Behaviors

Infant Button Pushes

A coder scored each time the infant pushed the button on the demonstration stimulus. A "button push rate" was calculated to control for differences in session length across dyads (see Maternal Modeling). The coder also scored when the infant pushed the button on the test stimulus, which was coded as *transfer success*. Reliability was 90% ($\kappa = 0.81$) for total number of infant button pushes, based on 20% of the data; however, reliability for transfer success was much higher (100%), based on 50% of the data.

Infant Activity Level

Because this study was conducted under semi-naturalistic conditions in infants' homes, infant activity level varied during the task. Low activity was coded if infants were primarily situated in one location (e.g., on the mother's lap), whereas moderate activity was coded if an infant frequently moved around the teaching task area. Reliability was 93% ($\kappa = 0.84$) based on 30% of the data.

Coding – Emotional Responsiveness

Emotional Responsiveness

To examine the reciprocal relationship between mother and infant, emotional responsiveness was coded on the basis of four global scales: shared focus, turn taking, maternal warmth, and infant involvement (adapted from Laible and Song, 2006; Fidler et al., 2010). For each dimension, dyads were rated on a five-point scale (with 1 = low amount of behavior and 5 = high amount of behavior) and anchor point definitions are provided next. Codes were not assigned for two mother–infant dyads in which the infants successfully transferred in less than 1 min; the session did not last long enough to accurately assess the measures.

Shared Focus

High shared focus was defined as a sense of togetherness, shared meaning, and unity with regard to the task; mother and infant "being on the same page." Low shared focus was defined as the mother and infant being engaged in completely different aspects of the task for the majority of the session, or a child who was engaged in off-topic play for most of the session. Reliability was 81% ($\kappa = 0.74$) based on 32% of the data.

Turn Taking

High turn taking was defined as the degree to which caregivers and infants engaged in conversational exchanges (verbal or non-verbal back-and-forth) with regard to the task. Low turn taking was defined by the absence of this type of exchange. Reliability was 81% ($\kappa = 0.70$) based on 32% of the data.

Maternal Warmth

High maternal warmth was defined as a mother's sensitive, engaging, and affectionate style toward her infant's affective cues; including promptness and appropriateness of reactions, physical affection, positive affect, tone of voice, and frequent encouragement and praise. Low maternal warmth was defined by frequent instances of frustration with the infant and no instances of encouragement or praise of the infant; a mother going through the motions of the task without engaging the infant. Reliability was 94% ($\kappa = 0.88$) based on 32% of the data.

Infant Involvement

High infant involvement was defined by consistent infant interactions with the mother and active verbal or non-verbal responses to a mother's directives or requests. Low infant involvement was defined by an infant being unreceptive to a mother's directives or requests. Reliability was 94% ($\kappa = 0.91$) based on 32% of the data.

Total Emotional Responsiveness

An overall emotional responsiveness score was calculated by summing the dyads' scores for each emotional responsiveness measure (maximum score = 20). Reliability was 88% ($\kappa = 0.82$) based on 32% of the data.

RESULTS

Analysis Plan

Preliminary analyses indicated that test condition (2D/3D or 3D/2D), average household media use (hours/day) or infant media use (hours/day), infant receptive or productive vocabulary (MCDI), parent education, socioeconomic status, or sex of child (male or female) did not show main effects or enter into any significant interactions. Therefore, these variables will not be discussed further, with the exception of test condition.

Transfer Success

Infants' transfer success on the touch screen task was 64% ($n = 32$). Transfer success did not differ by condition; 64% of infants were successful in the 2D/3D condition and 64% were successful in the 3D/2D condition. Although moderately high, transfer performance was well below ceiling.

Infant and Maternal Button Pushes

Infants pushed the button more often in the 3D/2D condition ($M = 2.87$, $SD = 1.75$) compared to the 2D/3D condition ($M = 1.81$, $SD = 1.76$). On the other hand, mothers modeled the button push more when the demonstration tool was the novel 2D touch screen image (2D/3D condition, $M = 3.44$, $SD = 2.22$) compared to when it was a 3D object (3D/2D condition $M = 2.28$, $SD = 1.36$), perhaps because the touch screen was a novel tool. That is, mothers adapted their demonstrations to meet the experience level of their infants.

Latency to Success

Infants who were not successful on the task ($n = 18$) automatically received the maximum total session time of 5 min. For those who were successful, the average latency to success from the time of first touch of the test stimulus was 1.57 min ($SD = 1.27$ min).

Infant Activity Level

Low activity level infants were significantly more likely to successfully transfer (75%; 24/32) than moderate activity level infants (37%; 6/16), $\chi^2(1, N = 48) = 6.4, p = 0.01$.

Stimulus Type

A chi-square analysis showed that infants tested with the bus (80%) were more likely to succeed than infants tested with the cow (48%), $\chi^2(1, N = 50) = 5.56, p = 0.02$.

Descriptive Statistics

Proportion of Diverse Verbal Input

Overall, mothers provided a good verbal teaching context. On average, 62% (*SD* = 12%; range = 39–92%) of mothers' utterances were new information. This finding is consistent with research examining mothers from middle to high SES, well-educated backgrounds in a teaching situation.

Maternal Structuring

Overall, mothers provided either optimal or moderate amounts of structuring in the teaching context. On average, just over half (54.2%) of mothers provided optimal structuring.

Emotional Responsiveness

Dyadic emotional responsiveness was on average at least a "3" (0–5 scale) for each individual measure for the infants who did and did not transfer (see **Table 2**). This indicates that high-quality emotional responsiveness within the dyad occurred during approximately half of the session time. On average, total emotional responsiveness within the dyad was 15.56 (*SD* = 3.58).

Interactional Quality

One of the main goals of the study was to examine whether mother–infant dyads exhibited different patterns of interactional quality during a touch screen transfer of learning task. Thus we conducted a K-means cluster analysis technique to classify cases into subgroups based on a set of specific attributes (Easterbrooks et al., 2005): emotional responsiveness, maternal structuring, and diversity of maternal verbal input.

The proportion of diverse maternal verbal input, total emotional responsiveness score, and amount of maternal structuring were chosen to enter into the cluster analysis because prior research has shown positive associations between mothers who respond and adapt to their infants' behaviors and vary their verbal input to match their infants' focus of attention, and later brain (Bernier et al., 2016) and cognitive development (e.g., DeLoache and DeMendoza, 1987; Rogoff, 1990; Farrant and Reese, 2000; Flynn and Masur, 2007). The cluster analysis included measures scored for 48 of the mother–infant dyads in the sample using a two-cluster model, as a sample size of 48 is sufficient for classifying cases into two clusters (Stata Manual, 2007). Cluster 1 ($n = 31$), was named *high interactional quality* with maternal teaching characterized as well-structured, a high proportion of diverse maternal verbal input, and high overall levels of emotional responsiveness within the dyad. Cluster 2 ($n = 17$) was named *moderate interactional quality* with maternal teaching characterized as moderately structured, a moderate proportion of diverse maternal verbal input, and moderate levels of emotional responsiveness within the dyad. **Table 3** shows the means for maternal teaching, the proportion of diverse verbal input, and emotional responsiveness as a function of each cluster.

Predictors of Infant Transfer

The second main goal of the task was to examine what specific elements of the task itself or mother–infant behaviors (i.e., interactional quality) may *predict* infant transfer success. Because infants could either succeed on the task or not, logistic regression was used for this analysis. The dependent variable was dichotomous; with '1' indicating infant success on the transfer task and '0' indicating the infant was not successful on the transfer task. The independent variables included were dyads' classification as high or moderate interactional quality, infant activity level, and stimulus (bus or cow); all variables were dichotomous.

The results of the logistic regression revealed that only the level of interactional quality was a significant predictor of infant success on the transfer task (**Table 4**). Infant activity level and stimulus were not significant predictors of infant transfer success. The significant odds ratio of 20.45 ($p = 0.01$) for interactional quality indicates that infants were 19 times more likely to succeed on the task if they were in a high interactional quality dyad, holding all other variables constant (**Table 4**). The accuracy of the prediction performed by the logistic regression was also evaluated using a classification table. Approximately, 87% of infants who

TABLE 2 | Mean emotional responsiveness ratings by infant transfer success.

	Transfer success			
	Infant transfer ($n = 30$)		No infant transfer ($n = 18$)	
Emotional responsiveness	***M***	***SD***	***M***	***SD***
Shared focus	4.27	0.87	3.17	0.99
Turn taking	3.93	0.94	3.11	0.90
Maternal warmth	4.40	0.81	3.83	0.71
Infant involvement	4.37	0.72	3.11	0.90
Overall	16.97	3.01	13.22	3.28

TABLE 3 | Maternal structuring, proportion of diverse maternal verbal input and overall emotional responsiveness as a function of interactional quality group.

	Interactional quality group			
	High interactional quality ($n = 31$)		Moderate interactional quality ($n = 17$)	
	M	***SD***	***M***	***SD***
Maternal structuring	1.68	0.60	0.18	0.53
Proportion diverse maternal verbal input	0.66	0.09	0.54	0.11
Overall emotional responsiveness	17.77	1.80	11.53	2.21

TABLE 4 | Results from logistic regression analysis of infant transfer success.

	B	*SE*	*P*	Odds ratio
Interactional quality group	3.02	1.21	0.01	20.45
Activity level	−0.60	1.25	0.63	0.55
Stimulus	1.23	0.78	0.11	3.42

B: unstandardized estimates; SE: standard error.

were predicted to be successful on the transfer task were in fact successful. Approximately 72% of infants who were predicted to be unsuccessful were not successful.

A standard linear regression analysis was also conducted with the same independent variables (interactional quality group, infant activity level, and stimulus) and infant latency to success (from the start of the session) as the continuous, outcome variable. Infants who did not succeed on the task were given a latency of 300 s, the maximum time allowed to complete the task. Initial collinearity diagnostics indicated that all Variance Inflation Factors were ≤2. The overall model for infant latency to success was significant, $F(4,43) = 6.36$, $p = 0.001$, $R = 0.55$, $R^2 = 0.30$. The pattern of results was identical to those found in the logistic regression analysis; only interactional quality group was a significant predictor of infant latency to success. Infants in the high interactional quality group took less time to successfully transfer compared to infants in the moderate interactional quality group.

DISCUSSION

This study builds on past research examining parent–infant interactions surrounding media use by (1) examining maternal scaffolding measures of verbal and non-verbal behavior, and interactional quality within each dyad and (2) measuring their relation to an immediate infant learning outcome in the context of a novel, touch screen teaching task.

Interactional Quality and Infant Transfer Success

Interactional quality, as measured by emotional responsiveness, maternal structuring, and diversity of maternal verbal input, significantly predicted infant transfer success. Infants in high interactional quality dyads were more likely to successfully transfer than infants in the moderate interactional quality dyads. In the presence of a supportive social partner, infants were just as successful when mothers were asked to teach from 3D to 2D as they were when mothers taught from 2D to 3D. Interactional quality seems to be especially important for infants because their representational, linguistic, and perceptual systems are still developing; therefore it can be challenging for them to integrate multiple sources of information on their own. This study showed that infants do not easily understand the functional equivalence between a 2D image and 3D object without additional support. In fact, 18 of the infants (36%) failed to transfer between 2D and 3D. This group was marked by lower amounts of emotional responsiveness within the dyad, less maternal structuring, and less diverse maternal verbal information.

Diverse Verbal Input

Mothers in high interactional quality dyads provided a higher proportion of diverse information compared to mothers in moderate interactional quality dyads. These mothers would either make a statement (e.g., this is a cow) and immediately elaborate on it (e.g., the cow says moo), or provide new information (e.g., you can push his button). In comparison, mothers in moderate interactional quality dyads did this less frequently, often providing the same piece of information multiple times in a row (e.g., this is a cow, see **Table 1**). Although, all mothers did revert back to providing some of the same verbal information that they used earlier in the task, the mothers of infants who transferred were not as repetitive in the sequencing of their verbal input. It is possible that mothers who varied their verbal input more frequently did so because they were better attuned to their infants' actions and interest in the task. These findings are consistent with studies examining mothers reminiscing with their preschool-aged children about the past (Fivush and Fromhoff, 1988; Hudson, 1990; Reese and Fivush, 1993).

Emotional Responsiveness

High interactional quality dyads were characterized by higher levels of turn taking and synchrony in their interactions. This illustrates the importance of not only the mother, but also the infant's involvement in the task. It was both the infants' verbal and non-verbal responses, and the mothers' sensitivity to their infants' interests that contributed to the high level of emotional responsiveness. Thus, infants might have benefited more from the verbal and non-verbal input of mothers who timed their behaviors to ensure they had their infants' attention (Tamis-LeMonda et al., 2001; Flynn and Masur, 2007). Emotional responsiveness consistently predicts future cognitive, language, and social outcomes (Bornstein, 1989; Tamis-LeMonda et al., 2001; Bornstein et al., 2008; Kaplan et al., 2009). Recent research has opened the possibility of a link between the quality of maternal behavior during mother–infant interactions and infant prefrontal brain development, the same area of the brain activated during executive function tasks (Bernier et al., 2016).

Consistent with the present findings, Ayoun (1998) found that the level of maternal responsiveness exhibited by mothers to their 11-month-olds during a free play session was significantly related to how well infants performed on a hidden object and contingency-based touch screen task. Ayoun proposed that infants who have been nurtured in predictable, responsive relationships with their caregivers are more likely to detect relationships between actions and goals in other contexts. Although, Ayoun's conclusions were speculative, they are consistent with the present findings.

Maternal Structuring

High interactional quality dyads were also characterized by mothers who provided optimal levels of structure. These mothers attempted to organize their infants' attention and interest in the task compared to moderate interactional quality dyads where mothers were more likely to provide too little or too much structure. Mothers' use of appropriate amounts of guidance and structure during the task is consistent with prior research showing a positive relationship between supportive parent–child interactions and young children's cognitive development (Rogoff, 1990; Farrant and Reese, 2000; Dodici et al., 2003).

One unpredicted finding was that mothers rarely used verbal matching strategies when teaching. Most mothers provided a verbal matching cue on at least one occasion (e.g., "this cow moos [2D] and this cow moos [3D])," but half of the mothers did so on fewer than five occasions. Given the correspondence between the 3D object and 2D image, it was surprising that most mothers did not capitalize on the side-by-side presentation of the 2D touch screen image and 3D object to accentuate their similarities. One possibility is that the perceptual similarity between the 2D image and 3D object was an obvious correspondence to the mother and because it was obvious to the mother she may have assumed it was also obvious to the child. Adults seamlessly navigate between 3D objects and 2D media tools (e.g., computers, television, smartphones) in their daily activities so they may be unaware of the difficulties infants face in transfer of learning across dimensions.

Limitations and Future Directions

There were three overall limitations of the touch screen teaching task that need to be addressed in future studies. First, there were limitations of task complexity and infant age. The one-step action chosen restricted the score to 1 or 0 and is limited to 15- and 16-month-old infants so the findings may not be generalizable to other age groups. Moreover, the types of teaching strategies that mothers employ would be predicted to change with age. Second, although responsiveness and structuring have been assessed in other studies using a 5-min task (e.g., Easterbrooks et al., 2005), it is still a short time period to fully assess these global ratings (Biringen et al., 2005). In this sample, only half of the mothers were still teaching during the fourth minute of the task. The raters also could not be completely blind to infant success on the task because of noticeable variations in session length – many of the infants who succeeded completed the task in less than 5 min time.

A semi-naturalistic task provides a good opportunity to investigate how interactional quality is related to transfer of learning from touch screens. Although, it was important to have an immediate outcome measure in this transfer of learning task, future research should also examine infants' ability to retain an understanding of the relationship between 2D and 3D by testing infants after a delay. From our data it is unclear how much the side-by-side presentation of the touch screen and 3D object contributed to infant transfer success, although the better transfer performance by infants in the high interactional quality group suggests success was not simply related to the nature of the task set-up. In future studies, specific aspects of the task that might have improved transfer can be experimentally manipulated to test their effects. Future transfer of learning studies should examine the facilitative effects of a side-by-side presentation of the 3D object and 2D touch screen image, increase the length of the demonstration and/or test, manipulate the amount and type of verbal and non-verbal input (e.g., pointing), and control the level of responsiveness provided by the mother or experimenter. Future studies should also explore whether infant success on the touch screen task is related to infant success on other 2D–3D transfer of learning tasks, such as learning from books or television.

Implications

Media use surveys show that infant touch screen use is on the rise. For children in the United States under the age of 2, 38% have used a mobile device; 51% of children have used smartphones and 44% tablets at least once by 2 years of age (Rideout, 2013). In a questionnaire study with low-income, minority families, Kabali et al. (2015) found that of children currently under age one, 92% had used a mobile device (e.g., smartphone, iPad, or tablet) whereas only 40% of current 4-year-olds used a mobile device before 1 year of age. This difference reflects an increase in mobile device use over 4 years time. They also found nearly 77% of children used mobile devices daily by age 2. Young children's widespread use of touch screens also extends beyond the USA (Neumann, 2014; Cristia and Seidl, 2015; Ahearne et al., 2016). Taken together, these findings show that in some communities, families are using interactive media early and often.

The benefits of high quality interactions during everyday activities such as feeding and book reading are consistently related to children's later cognitive and social development (e.g., Rogoff, 1990; Farrant and Reese, 2000; Hoff, 2003; Bernier et al., 2016). This is important with regard to infant learning from 2D media sources. If supportive interactions with infants during daily activities foster positive growth and development then it is reasonable to expect high interactional quality to be necessary for infant learning in media contexts with more novel forms of technology.

Hirsh-Pasek et al. (2015) proposed that we should draw from the Science of Learning field to understand how we can best promote children's playful learning from interactive devices. There are four components that need to occur for apps to be educational: cognitively active, engaged, meaningful, and socially interactive. These recommendations for app development arise from their general principles of guided play (for review see Weisberg et al., 2016). When infants successfully transferred, mothers were more likely to be cognitively active in that they promoted purposeful interaction; they kept their infant on task; they scaffolded their infant's existing knowledge; and they served as a contingent partner.

In sum, transfer of learning between 2D images and 3D objects is challenging for young children. The present findings suggest that for families in the digital age, the context in which infants learn from interactive technology is pivotal for transfer of learning between 2D touch screen and 3D sources. This research suggests that infants require input from an engaged, responsive social partner if they are going to understand the functional relationship between 2D and 3D sources. Parents should be educated about the challenges infants face in transferring information between touch screens and objects in their physical world. They should be encouraged to co-use media rather than rely on the touch screen as a stand-alone educational device, and use effective scaffolding techniques to enhance infants' transfer of learning from touch screens. Media has the potential to serve as an effective teaching tool that enhances learning in young children when used in supportive parent–child contexts.

AUTHOR CONTRIBUTIONS

This data was originally published as part of EZ's doctoral dissertation, *Infant transfer of learning across 2D/3D dimensions: a touch screen paradigm*. EZ developed the study concept, designed the study and data analysis plan, collected, analyzed and interpreted the data, and drafted the manuscript. RB developed and designed the study concept and data analysis plan, interpreted the data, and provided critical revisions. Both authors approved the final version of the manuscript for submission.

FUNDING

This research was supported by an Elizabeth Munsterberg Koppitz Fellowship to EZ from the American Psychological Foundation; NSF BCS 1023772 grant to Peter Gerhardstein and RB; and the Georgetown University Graduate School of Arts and Sciences.

ACKNOWLEDGMENT

Authors would like to thank the families for their participation and members of the Georgetown Early Learning Project for their help in data collection and Jadig Garcia for her help coding.

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Conflict of Interest Statement: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

ORIGINAL RESEARCH
published: 22 August 2016
doi: 10.3389/fpsyg.2016.01253

A Picture You Can Handle: Infants Treat Touch-Screen Images More Like Photographs than Objects

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Infants actively explore their world in order to determine the different ways in which they can interact with various objects. Although research on infant perception has focused on how infants understand the differences between 2- and 3-dimensional objects, today's infants increasingly encounter 2D images with interactive qualities on smart-phone screens, tablets, and laptops. The purpose of this experiment was to examine the types of manual behaviors infants direct toward tablet images and to compare these actions to those evoked by 2D photographs or 3D when tactile feedback is controlled. Infants between the ages of 7–10 months sat on their parent's lap in front of a table with a built-in well covered by a clear, plastic sheet while the three types of displays (photographs, objects, and screen images on a tablet) were presented for 30 s each. Infants saw three examples of each type of display presented in the built-in well so that tactile feedback information from the different displays was controlled. Coders noted the proportion of trials in which infants grasped, scratched, rubbed, or patted the display. Results indicate that infants direct significantly more grasps, scratches, and rubs toward 3D objects than 2D photographs. Infants also direct more grasps to objects compared to screen images. Our data suggests that infants are treating screen images more similarly to 2D photographs than 3D objects.

Keywords: infants, perception, touch-screens, perception and action, picture perception

OPEN ACCESS

Edited by:
Gabrielle Strouse,
University of South Dakota, USA

Reviewed by:
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Specialty section:
This article was submitted to Developmental Psychology, a section of the journal Frontiers in Psychology

Received: *27 May 2016*
Accepted: *08 August 2016*
Published: *22 August 2016*

Citation:
Ziemer CJ and Snyder M (2016) A Picture You Can Handle: Infants Treat Touch-Screen Images More Like Photographs than Objects. Front. Psychol. 7:1253. doi: 10.3389/fpsyg.2016.01253

INTRODUCTION

Is an object depicted on a touch-screen a picture, or an object? On one hand, it's a flat, 2-dimensional (2D) surface; on the other, the object depicted on the screen may respond to your touch by moving, growing bigger or smaller, making noise, or performing some other function. Images displayed on a touch-screen exist in a new realm somewhere between 3-dimensional (3D) objects and static, 2D images. Items depicted on touch-screens do not afford the same type of manual exploration as a 3D object, yet they offer more interaction than a static, 2D photograph. The prevalence of this new technology provides an interesting question in the world of infant picture perception. What do infants who encounter this type of technology understand about the properties of touch-screen displays? Do the ways in which infants explore screen-projected images reflect an understanding of their interactive nature?

Infants actively explore their world through touch and hand manipulation in order to determine the ways in which they can interact with various 2D and 3D objects. They touch, pat, bang, scratch, rub, and grasp at objects, and in doing so, gain an understanding of the object's properties and affordances for action. When manipulating images on a touch-screen phone or tablet, adults, and even young children display "screen-appropriate behaviors" (e.g., the "swipe," the "flick," and the "spread," Cristia and Seidl, 2015), showing that they understand the different properties of interactive screen images as compared to static screen images or photographs. However, touch-screen technology is relatively new and little is known about how young infants perceive the different affordances of touch-screens as compared to photographs and objects.

Infants have been shown to be sensitive to visual cues to depth (e.g., relative size, linear perspective, shading, texture gradient, etc.) as early as 5 months (Gordon and Yonas, 1976; Kavšek et al., 2009, 2012). When viewing virtual objects designed to appear closer or further away from the infant, infants reach more frequently to the nearer appearing object (Gordon and Yonas, 1976). When monocularly viewing 2D displays designed to create the illusion, via pictorial depth cues, of one display being closer than the other, infants will reach preferentially toward the nearer looking display. However, when viewing the same displays with both eyes, young infants are not fooled by the visual illusion and do not show preferential reaching (see Kavšek et al., 2009 for a meta-analysis on infants' sensitivity to pictorial depth cues via preferential-reaching studies).

As Goodale and Milner (1992) put forth, a dual-pathway visual system in the brain may explain the different reactions to stimuli seen as 3D (graspable) or 2D (non-graspable). Graspability dictates whether visual information is processed by the dorsal or ventral visual stream. If the object is perceived as being graspable, visual information will be processed dorsally (where binocular and motor responses are processed), if not, it will be processed ventrally (where pictorial information and perception judgments are processed). If infants as young as 5-month-old are sensitive to visual cues for depth, they should have a good sense of whether or not a display is 2D or 3D (i.e., not-graspable or graspable) based on depth cues if they are allowed to use both eyes to view the display. However, anecdotal reports of children "grasping" at 2D displays (images in a picture book or photographs) has prompted a line of research on this topic and suggests that there is still some manual exploration occurring as infants finalize their understanding of the different affordances of 2D and 3D objects.

A great deal of research in the field of infant picture perception has focused on understanding how infants perceive the differences between 2D and 3D objects and their ability to interact with and grasp these types of objects (e.g., DeLoache et al., 1998, 2003; Pierroutsakos and Troseth, 2003; Yonas et al., 2005; Ziemer et al., 2012). DeLoache et al. (1998, 2003) use the phrase "pictorial competence" to describe when infants understand that a picture is both an object in and of itself as well as a representation of what it depicts. When infants achieve this understanding of the dual nature of pictures and photographs they can begin to focus on the abstract, representational nature of photographs instead of the concrete aspects of the photograph itself (DeLoache et al., 1998). Therefore, younger children exhibit more manual exploration of photographs through rubbing, patting, and sometimes appearing to grasp at the images depicted; while older children respond with less manual exploration overall and exhibit more picture-appropriate behaviors such as pointing to the image (DeLoache et al., 1998; Pierroutsakos and Troseth, 2003).

Upon further investigation, Yonas et al. (2005) found that, when comparing the way 9-month-old infants reached toward various 2D depictions and objects, the shape of the infant's hand as well as the angle of the reach changed when infants were reaching toward a 2D depiction versus a 3D object. Infants reached with their hands higher when approaching an object than when approaching a photograph of an object. The angle and height of infants' reaching did not change when reaching for a photograph of an object compared to a non-pictorial (abstract) 2D display. This change in the hand approach for objects versus 2D displays indicates that infants may not be trying to "grasp," or pick up, the objects depicted in 2D images as DeLoache et al. (2003) suggest.

More recently, Ziemer et al. (2012) compared the manual behaviors that 9-month-old infants exhibited toward 3D objects and highly realistic 2D photographs when tactile feedback was controlled. Infants were presented with photographs and objects presented one-at-a-time under a Plexi-Glas® surface which covered a built-in well in the surface of a table. Coders noted the presence or absence of four types of actions—grasps, pats, rubs, and scratches—that infants directed toward the photograph and objects under glass. Ziemer et al. (2012) found that rubbing was the most frequent action followed by patting. For both of these frequent behaviors, there was no significant difference between the amount of rubs and pats directed toward 3D objects as compared to 2D photographs. However, when it came to the behaviors that might be considered more 3D-appropriate (grasps and scratches), Ziemer et al. (2012) found that 9-month-old infants directed significantly more of these behaviors toward objects than toward photographs. They concluded that by 9 months of age, infants are able to recognize and respond appropriately to the 2D photographs and 3D objects.

Today's infants are born into a world in which touch-screen technology is more prevalent than ever before. Parents and older siblings may have touch-screen phones and/or tablets that they use not only for voice calls, but video calls, taking photographs, and videos, checking weather, reading, and sending e-mails, playing games, and listening to music among many other functions. Infants are encountering interactive touch-screens with greater frequency and at earlier and earlier ages (Cristia and Seidl, 2015). Arguably, touch-screen displays are outside the scope of previous research on infants' understanding of the differences between 2D and 3D pictures and objects. Touch-screen images are 2D pictures projected on a flat surface yet they are able to be manipulated by touch. Therefore they are unlike static photographs and drawings and different from passive screen-images infants may encounter on television and movies. Touch-screen images break the rule that 2D depictions do not afford manual manipulation because they respond to specific forms of touch and encourage manual exploration.

In 2003, before touch-screen technology was as prevalent as it is today, Pierroutsakos and Troseth (2003) conducted a study examining the actions that infants direct toward stationary and moving videos presented on screens. They found that older infants (15 and 19 months old) exhibited less manual investigation and more pointing and vocalizing behaviors when exploring a screen image compared to 9-month-old infants who commonly grasped at, hit, and pat an image depicted on a screen. Pierroutsakos and Troseth (2003) also noted that the manual investigation behaviors that infants *do* display toward screen images may not be caused by infants confusing 2D images for 3D objects as the infants expressed little surprise or frustration at their inability to pick up an image. Rather, infants may be merely exploring the ways in which an image may be manipulated and learning about the concept of pictorial representation (Pierroutsakos and Troseth, 2003). A tendency for infants to manually explore flat surfaces may be especially useful as infants learn to use touch-screens that *can* be manipulated and respond to tactile interaction.

To date, there has been little descriptive or experimental research focusing specifically on infants' understanding of touch-screens as this technology as a common household item is fairly new. Research that has examined infants' exploration of screens has focused on passive screens which sit upright, facing the infant (like a television screen, e.g., Pierroutsakos and Troseth, 2003) instead of flat on a table as tablets and other touch-screens are usually used. Understanding how infants interact with touch-screen images is of growing importance. Both passive and interactive screen products such as movies, books, and games are being marketed for infants at a growing rate (Pierroutsakos and Troseth, 2003; Cristia and Seidl, 2015). Research into how infants understand this new kind of stimuli lags behind the creation of these programs. Currently, the American Academy of Pediatrics (AAP) recommends no screen time for children under the age of two; however, these guidelines came out before the release and popular usage of the iPad and tablets (Christakis, 2014). In order to understand the benefits or drawbacks of touch-screen products for young infants, we must first understand how infants perceive these screen images and how they fit into infants' schemas of 2D and 3D objects.

The following experiment examines how infants raised in today's culture perceive and interact with images presented on a tablet screen. The aim of this study was to determine if infants treat screen-displayed images more like passive 2D photographs or like interactive 3D objects. We observed the manual behaviors infants directed toward screen images on a tablet and compared them to the behaviors evoked by 2D photographs and 3D objects. Our methods replicate and extend those used by Ziemer et al. (2012) by controlling for tactile feedback with all three types of stimuli.

MATERIALS AND METHODS

Participants

Twenty-one infants (12 females) between the ages of 7-months and 10-months participated in this experiment. One infant was not included in the analyses because he was born over two months premature. The mean age of infants included in the analyses was 8 months 26 days. This age range was chosen in order to compare with previous infant picture perception research (e.g., DeLoache et al., 1998; Pierroutsakos and Troseth, 2003; Yonas et al., 2005; Ziemer et al., 2012) and because infants at this age have good depth perception and will reach for and explore objects (Gordon and Yonas, 1976; Yonas and Hartman, 1993; Kavšek et al., 2009). Infants were recruited for participation through an email sent to faculty at a Midwestern university, online Facebook groups for parents, and postings at local libraries and daycares.

Materials

Parents completed a questionnaire with nine items to assess screen usage and exposure. Three items examined how often the infant played games, watched movies, and played with a powered off device (e.g., Please indicate how often your child uses the following devices to play games or use apps). With these questions, a list of devices was given (TV/Video Games, Computer/Laptop, Tablet/iPad, and Cell Phone). For each device, activity was measured on a five-point scale from "never" to "several times a day." One item asked parents how often their infant operated devices without adult assistance. Two items explored infant exposure to screens without direct use through the amount of time primary caregivers spend on devices and number of screens (e.g., smart phones, televisions, computers, and tablets) in the home.

Objects, photographs, and screen images were presented to the infants during the experiment. Objects consisted of nine small infant toys with bright colors designed to attract an infant's attention. The photographs depicted the same nine toys printed on glossy white paper and affixed to foam board. These same nine images were also loaded onto a tablet device (Amazon Fire, 7-inch display) to create the screen images. Infants were shown three of each format– a total of nine trials for each infant. Objects, photographs, and screen images were all roughly the same size (approximately 4 inch × 3 inch).

The objects, photographs, and screen-images were presented in a table with a square, built-in well (8.5 inch × 8.5 inch) which was covered by a clear plastic (Plexi-Glass®) sheet. A white cushion in the well beneath the objects, photographs, and tablet allowed the displays to sit right up against the Plexi-glas®. The Plexi-glas® sheet was attached to the table with a hinge on the infant's side allowing the experimenter to raise and lower the sheet in order to change the display between trials. While the display was changed, a colorful piece of tag-board covered the Plexi-Glas® keeping the infant from observing the experimenter.

Thirty-second trials were timed by the experimenter using a hand-held stopwatch. Sessions were recorded using two Logitech web-cams (Tessar 2.0/3.7, 2MP autofocus) and the Panopto recording program (Windows computer compatible). Recordings were saved to a private Panopto folder only accessible to the experimenters.

Procedure

After signing the consent document and filling out the questionnaire on screen-use, infants and parents were brought into the lab. Infants sat on their parent's lap in front of a small table. The experimenter sat directly across the table from them. Parents were instructed to hold their child on their lap with their hands around their child's waist and not to interfere with their child's arms or touch the table themselves at any point. A short warm-up toy interaction between the experimenter and the child was used to make sure infants were able to reach the table where the displays would be presented. Parents were not informed about the purpose of the study, but were reminded that there was no "right" or "wrong" behavior their child should be exhibiting. It was also explained that their child was not participating in an assessment; rather their responses were merely being observed in order to gain a better understanding of infant perception.

Items were presented one-at-a-time for 30 s each. Each infant saw three photographs, three objects, and three tablet images in a randomized order. The presentation order as well as format for each toy presentation was randomized for each participant. Infants saw one version of each of the nine toys (i.e., they did not see both the photograph and object/screen image of the same toy). Each object was placed in the well on a cushion, so that it was directly beneath the Plexi-Glas® sheet. Photographs were attached to a piece of foam-board that fit the edges of the well, so they were pressed up to the plastic sheet as well. The tablet was also displayed on the cushion along with a piece of white poster board cut to frame the size of the image on the screen and to block the edge of the tablet from view.

Infants were allowed to explore each item for 30 s. If they seemed to have not noticed the item (e.g., had not looked at the item), the experimenter tapped on the table and verbally directed the infant's attention to the item. If an infant became fussy during the session, he or she would be allowed to take a break and then try to resume the session. Sessions were recorded from two different angles to allow different views for coding. At the end of the session, infants were given a toy to thank them for their participation.

Coding

Infants' manual behaviors toward the photographs, objects, and screen images were coded from the video recordings. Only manual behaviors that came in contact with the well area around the stimuli were counted. Coders recorded the presence or absence of pats, rubs, scratches, and grasps for each of the nine test trials. Pats were hand movements that came in contact briefly with the surface of the table (above the well area), either lightly touching or slapping. Rubs were hand movements that swept across the table coming in contact with the well area during some part of the movement. Scratches were hand movements in which one or more of the infant's fingers (usually the index finger) flexed and extended while in contact with the surface. Grasps were hand movements in which the infant's four fingers and thumb flexed closed into a fist while in contact with the table surface (see Butterworth et al., 1997; Ziemer et al., 2012). Coding for each trial began when the infant first looked at the photograph, object, or screen image and ended when the stimuli was covered up between trials. Inter-coder reliability ($N = 4$ infants) based on exact percent agreement (i.e., whether each action was present of absent on each trial) was 94.44%.

Proportion scores were computed by taking the number of trials of each type (photograph, object, and screen image) in which a given action occurred divided by the number of trials an infant completed for each trial type (see Yonas et al., 2005; Ziemer et al., 2012). The use of proportion allows even occasional behaviors to be represented in the data and is less subjective than counting the number of occurrences for each individual behavior.

RESULTS

Parents of the infants in this study reported having an average of 5.65 screens in their home ($SD = 2.01$, range 3–11). This included televisions, computers, smart phones, and tablets. The most common ways that parents reported their infants interacted with screen devices at home was by playing with powered-off phones and watching movies on a television. None of the parents in this study reported that their infants had ever used games or applications on a tablet, although a few parents reported that their children played games or applications on a phone, computer, or television. A few parents also reported that their infants occasionally watched movies on a computer or tablet and also interacted with these screens while the device was powered off. None of the parents included in the analysis reported that their infant ever used a screen device without supervision.

Figure 1 shows the mean proportion of trials in which infants directed grasps, scratches, rubs, and pats toward photographs, objects, and screen images. Overall, the most frequent action was rubbing, followed by patting. Grasping and scratching were relatively infrequent. The means proportion of trials infants grasped at the display was 0.07 ($SD = 0.137$) for screen images, 95% CI [0.01, 0.13], 0.12 ($SD = 0.163$) for photographs, 95% CI [0.05, 0.19], and 0.38 ($SD = 0.379$) for objects, 95% CI [0.21, 0.55]. The mean proportion of trials infants scratched at the display was 0.15 ($SD = 0.253$) for screen images, 95% CI [0.04, 0.26], 0.13 ($SD = 0.274$) for photographs, 95% CI [0.01, 0.25], and 0.32 ($SD = 0.333$) for objects, 95% CI [0.17, 0.47]. The mean proportion of trials infants rubbed the display was 0.68 ($SD = 0.333$) for screen images, 95% CI [0.53, 0.83], 0.63 ($SD = 0.388$) for photographs, 95% CI [0.46, 0.80], and 0.78 ($SD = 0.292$) for objects, 95% CI [0.65, 0.91]. The mean proportion of trials infant patted the display was 0.60 ($SD = 0.427$) for screen images, 95% CI [0.42, 0.79], 0.58 ($SD = 0.373$) for photographs, 95% CI [0.42, 0.74], and 0.68 ($SD = 0.350$) for objects, 95% CI [0.53, 0.83].

In order to determine whether 7–10-month-old infants performed different manual behaviors toward different types of depictions we first entered the proportion of grasps, pats, rubs, and scratches into an Display Type (3) × Action (4) repeated measures analysis of variance (ANOVA). The analysis yielded a significant effect of display type, $F(2,38) = 17.82$, $p < 0.0001$, and action, $F(3,57) = 23.71$, $p < 0.0001$. There was no significant Display × Action interaction $F(6,114) = 1.32$, $p = 0.253$, *ns*. Follow-up comparisons using the Bonferroni adjustment for multiple comparisons revealed that infants were rubbing significantly more than they were grasping ($p < 0.001$) and scratching ($p < 0.001$). Infants were also patting significantly more than they were grasping ($p < 0.001$) and scratching ($p < 0.01$). Infants directed significantly more behaviors toward objects than they did toward photographs ($p < 0.001$) or screen images ($p < 0.001$).

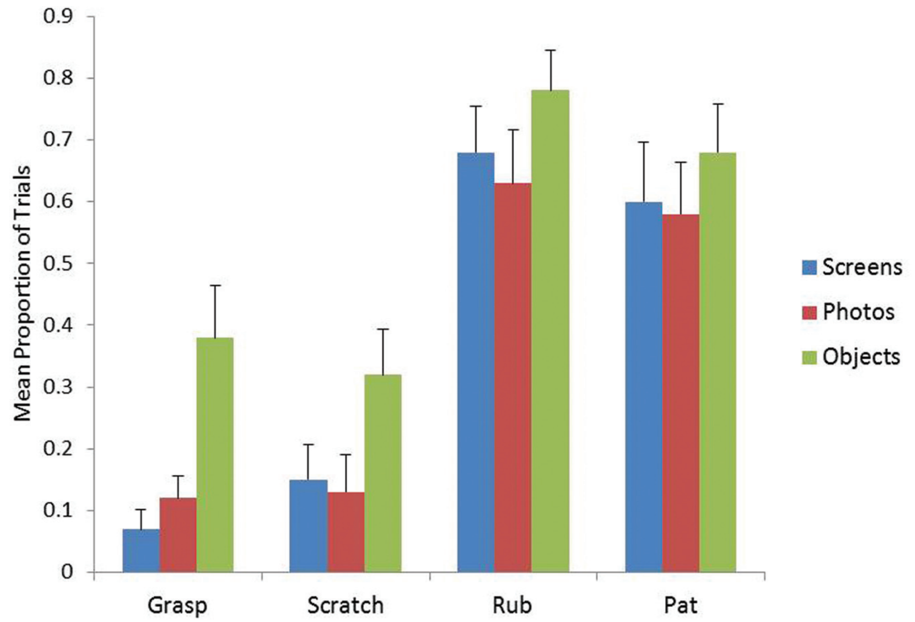

FIGURE 1 | Mean proportion of grasps, scratches, rubs, and pats directed to screens, photographs, and objects.

Protected paired-samples *t*-tests further revealed that infants directed a significantly higher proportion of grasps toward objects than they did toward photographs, $t(19) = -2.89$, $p = 0.009$, 95% CI [−0.46, −0.07], or screen images, $t(19) = 3.71$, $p = 0.001$, 95% CI [0.14, 0.50]. Infants also directed more scratches toward objects compared to photographs, $t(19) = -3.24$, $p = 0.004$, 95% CI [0.30, 0.06] and more rubs toward objects compared to photographs, $t(19) = -2.93$, $p = 0.009$, 95% CI [−0.26, −0.04]. No other differences were significant.

DISCUSSION

This experiment was designed to compare the manual behaviors infants displayed toward touch-screen images to the behaviors they direct toward objects and photographs. The infants in this study did not discriminate between the screen-images and photographs, showing similar types and amounts of behaviors toward screens as they did toward 2D photographs. Infants clearly showed a difference in the way in which they interacted with 3D objects as compared to photographs by directing more grasps, scratches, and rubs to objects than photographs. These results replicate the work by Ziemer et al. (2012) showing that, when tactile information is controlled, infants display different types of manual behaviors toward 2D and 3D displays. With the addition of a screen-image display, we were able to compare how, if at all, infants modify their behavior when a 2D image is presented on a screen. Our results indicate that, by 7–10 months, infants appear to understand that a screen-image is 2D, like a photograph. However, they do not appear to understand the interactive nature of touch-screens at this point in development.

One limitation of this sample was the fact that the infants tested had had little exposure to touch-screens. Although all of the families included in this study reported having several screens in their home, infants were not yet using these screens for interactive purposes. Movies and powered-off devices were the most frequent way infants were interacting with screens. Although it is possible (and quite likely) that the infants in this study have encountered social modeling by adults and older children interacting with touch-screen devices, the fact that they themselves had had little experience with the interactive nature of touch-screens may explain why the infants in this sample did not try to interact with the screen images more than static photographs.

In the future, it would be beneficial to our understanding of infant screen perception to recruit a more varied sample which better represents the population. The parents in our sample reported much less infant screen exposure than what has been reported in previous survey data (e.g., Kabali et al., 2015). This difference may have been caused by selection bias (e.g., the parents who had the time and inclination to bring their children to the university for a psychology study may be different from the population at large), or by bias in parents' reporting (e.g., under-reporting or under-estimating the amount of screen exposure their child has in order to be seen more positively). On the other hand, if, with a more varied sample, we still find little use of screens within this age group, it calls into question the findings from previous literature that infant screen use is as widespread as has been claimed (e.g., Kabali et al., 2015 finding that 43.5% of children under 1 year use a mobile device daily). Making the experimental set-up portable and taking it to places where more varied samples of children may gather (e.g., daycares, libraries, and preschools), may increase the sample variability with regard to screen exposure. This is one of the directions we are pursuing for future research in this area.

By 9 months, most infants have fairly good control over their arms and hands, but are still mastering fine motor movements of the fingers. This is the age at which infants begin developing the "Pincer grasp" which utilizes the thumb and index finger to pick up a small object such as a Cheerio (Gesell, 1952). It may be the case that the types of behaviors we exhibit toward touch-screens are too fine or complex for young infants to display even if they wanted to. Cristia and Seidl (2015) identified screen-specific behaviors such as "swipe," "flick," "tap," "press and drag," "pinch," and "spread," and asked parents in their study to report the frequency with which their children used these gestures while interacting with screens. Although some of these screen-gestures were very common (68% reported children doing a "flick," 71% reported the "tap"), the researchers noted that these behaviors, especially the more complex "pinch" and "spread," increased with children's age. Older children, with better dexterity and perhaps more screen experience, exhibited these behaviors with greater frequency than younger children (Cristia and Seidl, 2015).

In response to the concern that younger children may not have the dexterity to perform specific screen-appropriate manual behaviors toward an image depicted on a touch-screen, we are currently running a second group of infants between the ages of 15–18 months in the same experiment. A survey of parents by Kabali et al. (2015) found that 28.2% of 2-year-olds did not need any help navigating a mobile media device. It seems likely that between the ages of 1 and 2, as children's dexterity and cognitive ability increases, they also learn a great deal about the different ways that touch-screens afford interacting as opposed to pictures or photographs. Consequently, infants in this older age group may show more or different types of manual investigation when exploring an image depicted on a screen. Alternatively, as Pierroutsakos and Troseth (2003) found, older infants may display *less* manual investigation of a screen surface if they have learned that these types of images do not afford manipulation.

Although the parents whose children participated in this study reported that they were limiting their infants' exposure to screens before two years, many parents are either unaware or unable to stick to so strict a policy as put forth by the AAP. A survey of 350 children aged 6 months to 4 years by Kabali et al. (2015) found that 43.5% of children less than a year old and 76.6% of 2-year-old children used a mobile device daily to play games, watch videos, or use apps. Use of mobile devices by infants was not associated with child gender, ethnicity, or parent education. Parents in this study reported using the mobile devices to keep children entertained in order to do chores (70%), run errands (58%), calm their child down in a public setting (65%), or help their child fall asleep (28%; Kabali et al., 2015).

To be fair, it is nearly impossible to keep a child completely screen-free in today's society. Screens are everywhere—in the hands of adults making calls and taking photographs of their infant, on the laptop where relatives have FaceTime or Skype conversations with infants, televisions are becoming common fixtures in restaurants and waiting rooms (even some gas station pumps now show advertisements on built-in screens while the pump is running). With so many screens around, it is important to understand what effects different types of media may have on the development of young children and infants.

For example, the video deficit effect, (e.g., Zack et al., 2009), indicates that infants learn less from television and 2D images than from face-to-face interactions, suggesting an inability for transfer what is learned on screens into the real world. Further research is necessary to explain if a similar deficit in learning occurs with *interactive* 2D sources, such as touch-screen tablets. Concerns regarding the usage of iPads and tablets extend beyond the influx in tablet marketing for infants. The use of screens for purposes other than entertainment, such as regulating your child' mood, could have important implications for social and emotional development (Radesky et al., 2015). Impairment of the executive brain functions, which may be connected to ADHD, is implicated in screen overuse (Christakis, 2014). Researchers also fear that the use of iPads could inappropriately displace other enriching activities that provide active visual, language, and motor development (Radesky et al., 2015).

The results of this experiment indicate that, by 7–10 months, infants show little difference in their manual explorations of screen-projected images and 2D photographs. Although they occasionally may grasp or scratch at a screen image or photograph these behaviors are relatively rare and occur with much more frequency toward 3D objects. Our results suggests that infants are able to correctly perceive the flat surface of the screen and are not attempting to try to pick up the depicted object, treating it in the same way they treat a 2D photograph. To return to the idea of the dorsal/ventral visual pathway system (Goodale and Milner, 1992), it would appear that infants in our study were judging the screen images to be non-graspable (thus processed by the ventral stream as photographs are), rather than graspable (processed by the dorsal, action stream as objects may be). However, we still have much to learn about the ways in which young infants understand screen images and further experimental research examining different ages, different levels of screen experience, and different types of interaction with screens as well as long-term research into the effects of screen exposure during early years is needed to best advise parents of how to navigate this new world of touch-screens.

AUTHOR CONTRIBUTIONS

Both CZ and MS were involved in the design of this experiment, data collection, coding, data analysis, and writing of this document.

ACKNOWLEDGMENT

This work was completed in part with help from a PORTAL summer research grant awarded to Dr. CZ by Missouri Western State University PORTAL committee.

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Conflict of Interest Statement: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

frontiers in Psychology

PERSPECTIVE
published: 12 August 2016
doi: 10.3389/fpsyg.2016.01220

Children's Learning from Touch Screens: A Dual Representation Perspective

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Parents and educators often expect that children will learn from touch screen devices, such as during joint e-book reading. Therefore an essential question is whether young children understand that the touch screen can be a symbolic medium – that entities represented on the touch screen can refer to entities in the real world. Research on symbolic development suggests that symbolic understanding requires that children develop dual representational abilities, meaning children need to appreciate that a symbol is an object in itself (i.e., picture of a dog) while also being a representation of something else (i.e., the real dog). Drawing on classic research on symbols and new research on children's learning from touch screens, we offer the perspective that children's ability to learn from the touch screen as a symbolic medium depends on the effect of interactivity on children's developing dual representational abilities. Although previous research on dual representation suggests the interactive nature of the touch screen might make it difficult for young children to use as a symbolic medium, the unique interactive affordances may help alleviate this difficulty. More research needs to investigate how the interactivity of the touch screen affects children's ability to connect the symbols on the screen to the real world. Given the interactive nature of the touch screen, researchers and educators should consider both the affordances of the touch screen as well as young children's cognitive abilities when assessing whether young children can learn from it as a symbolic medium.

Keywords: touch screen, symbol, symbolic medium, dual representation, tablets, symbolic understanding

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Specialty section:
This article was submitted to Developmental Psychology, a section of the journal Frontiers in Psychology

Received: *30 May 2016*
Accepted: *02 August 2016*
Published: *12 August 2016*

Citation:
Sheehan KJ and Uttal DH (2016) Children's Learning from Touch Screens: A Dual Representation Perspective. Front. Psychol. 7:1220. doi: 10.3389/fpsyg.2016.01220

INTRODUCTION

Since the introduction of touch screen technology, new media platforms such as tablet computers and other handheld devices have been marketed to and widely used by children of young ages (Common Sense Media, 2013). Compared to other technologies used by children, touch screen devices are unique because children can use them in many ways, such as for watching videos, e-book reading, Skyping with grandparents, and more. For many of its uses, such as e-book reading and watching videos, learning from the touch screen requires that children appreciate the symbolic nature of the touch screen. Children can learn by connecting the entities depicted on the screen with their referents in the real world. But does the child understand that the animals they learned about in the e-book represent animals in the real world? Can the child connect concepts learned from a video on a touch screen to her everyday experiences?

For traditional symbols, such as pictures and text, making the leap from symbol to referent requires that children develop *dual representation* – they must represent both that the symbol is a concrete object while also representing that the symbol refers to something other than itself (DeLoache, 1989; DeLoache et al., 1997). However, the touch screen is not a traditional symbolic medium. It is unique in that it is interactive; children can directly manipulate the screen, which responds instantly to their touch. However, being able to manipulate the screen does not necessarily mean children can learn from it. We review traditional symbolic research that suggests manipulating the touch screen may lead children – specifically toddlers and preschool-aged children – to focus on the screen itself rather than on what the entities on the screen represent (DeLoache, 2000). But in contrast, we also review more recent research that suggests the interactivity may help children connect entities on the screen to their referents, perhaps allowing them to circumvent the potential difficulty caused by dual representation.

The purpose of this paper is to consider both the potential negative and positive effects of touch screen interactivity on children's ability to understand the symbolic nature of entities represented on the screen, but it is important to note that the potential effects likely depend on children's age and the touch screen activity. For example, in this paper, we discuss the possibility that interactivity may hinder preschool-aged children's learning from a symbol they typically learn from without interactivity, but may promote learning for toddlers who typically struggle to learn from that symbol. Additionally, the touch screen can be used for many different symbolic activities, some of which are interactive (e.g., reading an interactive e-book) and some of which are not (e.g., watching a video). In this paper, we take the perspective that interactivity alters how children view the touch screen as a symbolic medium, and therefore affects their symbolic learning from both interactive and non-interactive activities. However, it is possible that children learn differently from interactive versus non-interactive activities. While this perspective will not expand on all these possibilities, we do discuss the general potential effects of interactivity, age, and touch screen activity on children's symbolic transfer from the touch screen.

THE EFFECT OF INTERACTIVITY ON DUAL REPRESENTATION

It is often difficult for young children to "see through" a symbol to the referent that it represents (DeLoache, 2000). Instead children often focus on the symbol itself rather than on the entity it refers to. For example, 9-month-old infants will physically manipulate a picture, treating the picture like the object it represents rather than appreciating it as merely a representation (DeLoache et al., 1998; Pierroutsakos and DeLoache, 2003). Similarly, when asked to use a scale model to find a hidden object in a larger room, 2.5-year-olds fail to use the model as a representation but succeed in finding the object when they are made to believe that the model magically grew to be the room (DeLoache, 1987; DeLoache et al., 1997). In both of these cases, children's symbolic failure stems from a lack of dual representation; they focus on the symbol as an object in itself rather than on it being a representation for something else.

Considering children's difficulty with dual representation, emphasizing a symbol's status as an object or entity can hinder children's understanding and use of that symbol, while de-emphasizing its status as an object can promote children's symbolic use. For example, DeLoache (2000) found that when children were asked to use a scale model as a symbol for a room, 2.5-year-olds' performance was facilitated when the model was put behind glass, which prevented them from playing with model and therefore helped them view the model as a representation and not as a toy. In addition, 20-month-old infants learned fewer novel labels for three-dimensional pictures in a pop-up book compared to two-dimensional pictures in a traditional picture book (Tare et al., 2010). Here, making the pictures three-dimensional – and therefore objects – hindered toddlers' symbolic learning. When children view a symbol as an appealing object, it is more difficult for them to represent both that object and the referent that it represents. Symbols that are salient physical entities are more difficult for children who are developing dual representational abilities to understand.

However, it is not just concrete objects that can hinder young children's dual representation of symbols; two-dimensional screens can also pose a dual representation problem for young children. Many researchers have suggested that children's difficulty with the dual representational nature of the screen is one reason why young children often struggle to learn from video, a phenomenon that has been termed the *video deficit effect* (Anderson and Pempek, 2005; see also Barr, 2010; Krcmar, 2010). For example, 24-month-old infants struggle to use a video of an object being hidden in a room to find the object, but succeed in using the video when they are made to believe they are directly seeing the toy being hidden in real life (Troseth and DeLoache, 1998; Schmitt and Anderson, 2002). Much other research shows that young children are relatively poor at learning information presented on a television compared to learning from a face-to-face interaction with a person, such as imitating an action sequence (Barr and Hayne, 1999) or learning new words (DeLoache et al., 2010). To young children, the image on the screen is just an image. They may not realize that the image can inform them about objects and actions in their lives. Therefore young children need to learn to appreciate that a video image is not just something on television, but also potentially represents something real.

The cost of appealing symbols, as well as children's difficulty learning from screens, suggests that the interactive affordance of touch screens may pose a symbolic impediment for young children because it may lead children to focus on the screen that they are manipulating rather than on what the image on the screen stands for. Children interact with the touch screen in a way that may lead them to conceptualize the screen as being an appealing object. Therefore, because the touch screen is designed to be manipulated, young children's interaction with it may lead them to focus on the touch screen itself rather than on what the images on the screen represent. Interactivity may emphasize that the screen is an object in its own right rather than as a medium for representing objects.

Touch screens may pose a problem for dual representation not only because of their interactive features, but also because they are multimodal and are often used for playing games, which may lead children to conceptualize the device as being a toy. Toys are especially appealing objects, which means it is very difficult for children to see through toy-like symbols to the referents they represent. For example, research shows that when children are asked to use a toy such as a doll as a symbol, 2.5-year olds perform poorly when asked to map between the doll and their own body (DeLoache and Marzolf, 1995; Herold and Akhtar, 2014). Strong evidence for the disadvantage of toy-like symbols come from a study in which 3-year-olds played with a scale model like a toy for 10 min before using it as a symbol to find a hidden object in a larger room (DeLoache, 2000). While 3-year-olds typically found the hidden object on 75 percent of their searches, playing with the model beforehand led children to find the hidden object on only 44 percent of their searches. In the same way that 3-year-olds' use of a scale model as a toy hindered their understanding of it as a symbol, young children's use of a touch screen device as a toy may hinder their later understanding of the screen as a symbolic medium.

If children use touch screens as toys by playing games on them, they may form expectations about the devices as being a form of entertainment rather than a tool for learning. Children's expectation about a video has been shown to affect their ability to learn from it as a symbol. For example, research shows that children imitated less from a video viewed on their own television (that they usually used for entertainment) compared to an unfamiliar video monitor in a laboratory (Strouse and Troseth, 2008). Children's previous (and possibly more frequent) experiences using a two-dimensional screen as an appealing source of entertainment may hinder their later ability to use it as a symbol. Therefore, children's interaction with touch screens, their conceptualization of them as toys, and the subsequent expectations they form about the purpose of touch screens are all possible reasons why children may struggle to learn from symbols represented on the touch screen.

CAN INTERACTIVITY ALLEVIATE THE NEED FOR DUAL REPRESENTATION?

Despite the implications of research on traditional symbols and symbolic media, there are reasons to believe that the interactivity of the touch screen may not hinder children's understanding of it as a symbolic medium, but rather may promote children's learning from the symbols represented on the screen. As mentioned above, the touch screen is a unique symbolic medium, and is almost entirely different from other symbolic media because it immediately responds to the child's touch. Although, we can draw upon research on traditional symbolic media to make inferences about the possible effects of interactivity on children's symbolic understanding, the touch screen's interactivity may set it entirely apart, meaning the results of previous research may not generalize to it. The touch screen may be in an entirely unique symbolic class of its own.

In this section, we consider the potential positive effects interactivity may have on children's ability to learn from the touch screen. It is possible that the interactive nature of the touch screen can actually promote children's symbolic use of it because the interactivity links the screen with the child's experiences in the real world. From this perspective, the interactive aspect of the touch screen does not create an impediment for dual representation, but actually reduces or circumvents the need for dual representation. Research shows that children learn better from characters or people on a screen when they are *socially contingent* to the child – or in other words, when they are responsive to a child's actions or vocalizations (Troseth et al., 2006; Krcmar, 2010; Roseberry et al., 2014). Contingency is important because it helps the child realize that the person or entity on the screen is relevant to the child, and therefore that the child can learn from that person or entity. The physical contingency of the touch screen may help children learn from it in a similar way: The screen's immediate response may help children see a symbol as relevant and therefore focus their attention on it – and not other irrelevant entities on the screen. If contingency helps children focus their attention on a particular symbol on the screen, it may help them connect the symbol to its referent and not to other entities that are present.

Importantly there is evidence that interactivity helps children learn from screen media. Lauricella et al. (2010) asked 2.5- to 3-year-olds to participate in a hide-and-seek game in which children either observed an adult finding a hidden object, watched a video revealing where the object was hidden, or played an interactive computer game in which a keyboard response revealed where the object was hidden in the room. When children later searched the room themselves, the 3-year-olds who played the interactive computer game performed just as well as those who observed an adult, and both groups performed significantly better than those who passively watched a video. Although this study did not include a touch screen device, the results suggest that the contingent nature of the game facilitated children's appreciation of the symbol-referent relation compared to passively watching a video, and that interactivity may be an important means by which young children learn from screen media.

More recent research by Kirkorian et al. (2016) suggests that the contingency of touch screen devices may indeed promote children's symbolic understanding, but the benefits of interactivity may depend on age. The researchers asked 2-year-olds to watch a video of a person on a touch screen label a novel object, and either had children passively watch, tap anywhere on the screen to hear the label, or tap the location of the object on the screen to hear the label. The researchers found that while tapping the location of the object facilitated word learning for younger 2-year-olds, this manipulation hindered learning for older 2-year-olds who learned the novel word when they passively watched with the video. Choi and Kirkorian (2016) also found a similar effect of contingency and age in an object-retrieval task in which children either passively watched on a touch screen where an object was hidden on a felt board, tapped anywhere on the touch screen, or tapped a specific location on a touch screen to reveal the hiding location. Again, younger 2-year-olds were better at retrieving the object on a corresponding felt board when they tapped a specific location, but older 2-year-olds performed worse when tapping a specific location compared to the other conditions. The researchers suggest that the interactivity benefitted the younger 2-year-olds by guiding their selective attention to target information, but it hindered older 2-year-olds' performance because the contingency led to over-contextualization: their learning became tied to the context in which the learning took place, which impeded their symbolic transfer.

This research highlights the perspective that touch screens' interactivity may promote children's ability to connect objects represented on the screen with their referents, and also suggests the influence of interactivity on symbolic understanding may depend on age and the specific touch screen task. For example, Zack et al. (2009) found that 15- to 16-month-old infants could imitate a novel action performed on an object represented on a touch screen, but struggled to transfer that action to a three-dimensional object (see also Barr, 2010). In comparison, the younger 2-year-olds in Choi and Kirkorian (2016) could transfer from a two-dimensional interactive screen to a three-dimensional apparatus. Depending on the symbolic touch screen activity (e.g., learning new words, learning actions for objects), interactivity may have different effects for different ages.

SUMMARY AND CONCLUSION

In this paper, we considered the possibility that the interactive nature of the touch screen may affect children's ability to learn from it as a symbolic medium. First, we adopted a traditional symbolic perspective: interactivity may make the touch screen an appealing object to children, which increases the need for dual representation and therefore may render it a difficult symbolic medium for young children to learn from. For example, research on children's symbolic understanding of dolls, pop-up picture books, and scale models provide support for the view that emphasizing the toy-like, object status of these symbols hinders children's ability to learn from them (DeLoache and Marzolf, 1995; DeLoache, 2000; Tare et al., 2010). In the same vein, we suggest that the manipulative, toy-like use of the touch screen may affect the way children conceptualize and form expectations about it. It may be difficult for young children to look past their entertainment value while also appreciating that the entities on the screen can represent real objects or entities, and therefore be used for learning.

However, we also considered the perspective that the very aspect of touch screen devices that may create an impediment for children – the touch screen itself – may also help children connect symbols on the screen to their referents in the world. Touch screens may promote learning by providing a contingent response, which has been shown to help children learn from other symbolic media, such as computers and video, and may help focus children's attention on the symbol. This possibility is supported by recent research that shows that interacting with a touch screen promotes 2- and 3-year-old children's ability to connect a symbol on the touch screen to its referent (e.g., Choi and Kirkorian, 2016; Kirkorian et al., 2016). This research also suggests that the effect of interactivity may depend on age; for older children, interactivity may be more distracting than helpful, largely because older children may already be able to transfer from the touch screen during certain touch screen activities without interacting with it.

Nonetheless, it is important to continue pursuing research that is aimed at understanding how the effect of interactivity may change with age and the symbolic touch screen activity (e.g., interactive vs. non-interactive). With more research, educators, parents, and researchers will be better informed of how the unique affordances of the touch screen affect children's ability to "see through" it as a symbolic medium. Ultimately it can help them assess the value of the touch screen as a symbolic medium, which has implications for its value as a tool for learning at different ages. While the interactive appeal of touch screens may directly impede upon children's ability to learn from them, it is possible that the interactivity of touch screens may be the very feature that helps children connect symbols on the screen to their referents in the real world.

AUTHOR CONTRIBUTIONS

KS contributed to the conception of the work, the intellectual content, the drafting the work, and gave final approval of the version to be published. DU also made substantial contribution to the conception and intellectual content of the work, editing and revising it, and gave final approval of the version to be published. Both KS and DU agree to be accountable for the content of this work.

FUNDING

This article was funded by NSF SLC Grant SBE0541957, The Spatial Intelligence and Learning Center.

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Conflict of Interest Statement: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

frontiers in Psychology

ORIGINAL RESEARCH
published: 02 August 2016
doi: 10.3389/fpsyg.2016.01108

Toddlers' Fine Motor Milestone Achievement Is Associated with Early Touchscreen Scrolling

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Touchscreen technologies provide an intuitive and attractive source of sensory/cognitive stimulation for young children. Despite fears that usage may have a negative impact on toddlers' cognitive development, empirical evidence is lacking. The current study presents results from the UK Toddler Attentional Behaviours and LEarning with Touchscreens (TABLET) project, examining the association between toddlers' touchscreen use and the attainment of developmental milestones. Data were gathered in an online survey of 715 parents of 6- to 36-month-olds to address two research questions: (1) How does touchscreen use change from 6 to 36 months? (2) In toddlers (19–36 months, i.e., above the median age, $n = 366$), how does retrospectively reported age of first touchscreen usage relate to gross motor (i.e., walking), fine motor (i.e., stacking blocks), and language (i.e., producing two-word utterances) milestones? In our sample, the proportion of children using touchscreens, as well as the average daily usage time, increased with age (youngest quartile, 6–11 months: 51.22% users, 8.53 min per day; oldest quartile, 26–36 months: 92.05% users, average use of 43.95 min per day). In toddlers, aged 19–36 months, age of first touchscreen use was significantly associated with fine motor (stacking blocks), $p = 0.03$, after controlling for covariates age, sex, mother's education (a proxy for socioeconomic status) as well as age of early fine motor milestone achievement (pincer grip). This effect was only present for active scrolling of the touchscreen $p = 0.04$, not for video watching. No significant relationships were found between touchscreen use and either gross motor or language milestones. Touchscreen use increases rapidly over the first 3 years of life. In the current study, we find no evidence to support a negative association between the age of first touchscreen usage and developmental milestones. Indeed, earlier touchscreen use, specifically scrolling of the screen, was associated with earlier fine motor achievement. Future longitudinal studies are required to elucidate the temporal order and mechanisms of this association, and to examine the impact of touchscreen use on other, more fine-grained, measures of behavioral, cognitive, and neural development.

Keywords: touchscreen, tablet, infant, toddler, developmental milestones, fine motor

OPEN ACCESS

Edited by:
Jordy Kaufman, Swinburne University of Technology, Australia

Reviewed by:
Rachel Barr, Georgetown University, USA
Heather Kirkorian, University of Wisconsin-Madison, USA

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Specialty section:
This article was submitted to Developmental Psychology, a section of the journal Frontiers in Psychology

Received: *13 April 2016*
Accepted: *11 July 2016*
Published: *02 August 2016*

Citation:
Bedford R, Saez de Urabain IR, Cheung CHM, Karmiloff-Smith A and Smith TJ (2016) Toddlers' Fine Motor Milestone Achievement Is Associated with Early Touchscreen Scrolling. Front. Psychol. 7:1108. doi: 10.3389/fpsyg.2016.01108

INTRODUCTION

Family ownership of touchscreen devices such as tablets and mobile phones has increased in the UK from 7% in 2011 to 71% in 2014 (Ofcom, 2014). Touchscreens provide an intuitive and attractive source of sensory and cognitive stimulation for young children (Cristia and Seidl, 2015), and the impact of such devices on children's development is a pressing question of concern to parents, scientists, and policy makers. Several prominent voices have sparked fears in the popular press about the negative impact of such technology (e.g., Carr, 2010; Sigman, 2012; Greenfield, 2015), with one of the most prominent parent-advisory agencies, the American Academy of Pediatrics (AAPs), advising zero screen time before the age of 2 years (Brown, 2011; Strasburger and Hogan, 2013; although the AAP are currently in the process of revising the guidelines). This guideline has been adopted by other government agencies around the world, including in the UK (Public Health England, 2013), Canada (Lipnowski et al., 2012), and Australia (Australian Department of Health and Ageing, 2014). However, empirical evidence relating early touchscreen use in toddlerhood to delays in cognitive development is currently lacking. Here, we examine the relationship between touchscreen use and the achievement of developmental milestones, using data from a large UK survey: the Toddler Attentional Behaviours and LEarning with Touchscreens (TABLET) project.

In line with Ofcom's (2014) report pointing to a sharp increase in the prevalence of household touchscreen devices (Ofcom, 2014), recent studies suggest that the majority of infants and toddlers have experienced some degree of exposure to touchscreens (Ahearne et al., 2015; Cristia and Seidl, 2015; Kabali et al., 2015). In a sample of 450 babies from a French babylab (Cristia and Seidl, 2015), 58% of 5- to -24-month-old infants had used a touchscreen. This is in comparison to an earlier report that 33% of American infants (birth to 2 years of age) had used a touchscreen (Rideout, 2013). Frequency of use across these two samples was similar, with just over 20% of infants and toddlers experiencing daily use of the touchscreen. A more recent study using a low income ethnic minority American sample reported much higher frequencies with 75% of children using a touchscreen device daily by 2 years of age (Kabali et al., 2015). This percentage was mirrored (71%) in a diverse socioeconomic status (SES) hospital-based sample of 12–36 month-olds from Northern Ireland (Ahearne et al., 2015).

The type of touchscreen usage also changes with age (Cristia and Seidl, 2015). Parents report that around 75% of toddlers use touchscreens to look at photos or to watch videos, with about 50% actively playing baby-friendly apps. The increase in active use may be due to developing fine-motor skills (e.g., precise finger control), increasing executive function required to understand the touchscreen interface, as well as the developing need for more structured sensory reward and stimulation. Motor developments are demonstrated in the gestures toddlers use to interact with a screen such as banging the screen (16%), tapping (71%), dragging (41%), swiping (20%) and pinching (10%), with all gestures increasing with age (with the exception of a decrease for the non-deliberate banging gesture; Cristia and Seidl, 2015) together with the child's need for parental assistance decreasing from 71.8% at 2 years to 57.1% at 4 years of age (Kabali et al., 2015). These usage statistics suggest that the frequency, type, and complexity of touchscreen use develops along with general cognitive development. However, it is not currently known if and how the two developmental strands interact.

How might toddler touchscreen use influence cognitive development? Given the relatively recent introduction of touchscreen devices into the developmental environment of children, there is currently no research directly assessing the impact of touchscreen use on early cognitive development. Empirical evidence from more established media, namely TV viewing and videogames, suggests that TV screen time is associated with delayed language (Zimmerman et al., 2007), poorer health (Strasburger et al., 2012), and attentional problems (Christakis et al., 2004). However, several of these effects have been shown to be moderated by factors such as parenting style (Linebarger et al., 2014), type of content (Linebarger and Walker, 2005) or coviewing with a parent (Mendelsohn et al., 2010) and may disappear when confounds such as SES are factored in Schmidt et al. (2009). Evidence for the impact of actively playing videogames is similarly mixed. Increased gaming in older children is related to greater parent/teacher-reported attentional problems (Swing et al., 2010), as well as memory and sleep problems (Dworak et al., 2007) but has also been shown to increase performance on cognitive tests including enhanced visual processing, attentional, and motor control in adults (Green and Bavelier, 2008).

Touchscreens combine the interactivity of a videogame with the non-interactive entertainment of television, but less is known about the direct impact of touchscreen use on behavior than these two established forms of media. One recent study in adults showed that touchscreen phone users (compared to non-users) have greater activation of the somatosensory cortex in response to a mechanical touch to the thumb, index finger, and middle finger (Gindrat et al., 2015). However, increased time spent with a touchscreen may also have detrimental effects on physical activity and language. The *displacement hypothesis* (Strasburger et al., 2012) states that the time a child spends engaged with a screen limits the time they have to do other activities, leading to reduced physical activity (Sisson et al., 2010; although see Taveras et al., 2007) and reduced face-to-face communication (Huttenlocher, 1998; Hart and Risley, 2003; Rowe, 2012; Sosa, 2016).

To our knowledge, no studies have directly assessed the impact of touchscreen use on toddlers' developmental milestones. Critically, touchscreen devices can be easily used by children with relatively immature cognitive and behavioral abilities, at an age when neural development and plasticity is high (e.g., Huttenlocher, 2002). As with TV and videogames, the impact of touchscreen use on development is likely to be mixed depending on the type of use (Hirsh-Pasek et al., 2015). In the current paper we examine two main research questions: (1) How does touchscreen usage change with age across our full sample of 6- to 36-month-olds? (2) In toddlers (aged 19–36 months), is retrospectively reported age of first touchscreen usage associated with developmental milestones: gross motor (i.e., walking), fine motor (i.e., stacking blocks), and language (i.e., producing two-word utterances)?

MATERIALS AND METHODS

Participants

In total, 715 UK-based parents of 6- to 36-month-old children completed an online questionnaire asking questions about demographic information, their child's media usage and retrospectively reported developmental milestones. The questionnaire was administered between June 2015 and March 2016. The final sample size used in each analysis varied due to missing data for certain questionnaire elements (see **Table 1**). Parents were recruited via the Birkbeck Babylab database, Goldsmiths' Babylab database and study advertisements from various news agencies, magazines and agencies including National Childbirth Trust (NCT). The study was approved by the Birkbeck Psychological Sciences' ethics board.

Demographic Information

Information was collected about the child's age (mean age = 19.52 months, *SD* = 8.26 months) and sex (336 females), as well as mother's educational level (a proxy for family SES; "What is the highest degree or level of education the mother of the child has completed?" Responses were "Not applicable," *N* = 3; "School leaving qualification," *N* = 20; "College," *N* = 79; "University," *N* = 294; and "Post-graduate," *N* = 319).

Touchscreen Usage

Media questions were derived from existing questionnaires investigating touchscreen usage (Rideout, 2013; Linebarger et al., 2014; Ofcom, 2014). Parents were asked about (1) number of devices: 'How many touchscreen devices do you have in your home?' and 'How many of these touchscreen devices belong to your child?; (2) frequency of child's use: 'On a typical day, how long does your child spend using a touchscreen device?'; and (3) age of first use: 'How old was your child when he/she first did the following activities on a touchscreen device… Scrolled or touched the screen/Passively watched videos.'

Developmental Milestones

In order to assess the onset of key developmental milestones without having to complete an entire standardized assessment (e.g., Vineland Adaptive Behavior Scales, VABS-II; Sparrow et al., 2005), critical milestones from motor and language domains were chosen. All questions took the format: 'At what age did he/she first…' and in the current paper, we use data from one 'early' and one 'late' milestone, e.g., 'Sit without support' and 'Walk independently' (gross motor), 'Pick up a small object with a pincer grip, i.e., with thumb and forefinger' and 'Stack at least three small blocks or other small objects; stack must not fall' (fine motor), 'Say their first word' and 'Put two or more words together' (language).

Statistical Analysis

Data were initially cleaned using scripts in SPSS (Ver. 22, IBM Corp., 2013) to remove any impossible values due to entry errors, e.g., more than 24 h per day on a touchscreen. In addition, one child's reported daily touchscreen usage time was removed from the current analyses (a clear outlier of 1200 min per day which was > 19 SD above the mean). Analysis was performed using SPSS and Stata 13 (StataCorp, 2013).

TABLE 1 | Descriptive statistics: parent reported touchscreen use and developmental milestones in 6- to 36-month-olds.

	Age quartiles				Total	Total
	6–11 m	**12–18 m**	**19–25 m**	**26–36 m**	**6–36 m**	**19–36 m**
Age (months)						
M	8.99	14.40	21.94	30.64	**19.52**	**26.39**
(SD)	(1.82)	(2.19)	(2.07)	(3.07)	**(8.26)**	**(5.08)**
N	134	215	179	187	**715**	**366**
Own touchscreen (percentage)						
%	0	5.67	11.03	21.19	**9.62**	**16.22**
N	123	194	145	151	**613**	**296**
Touchscreen use (percentage)						
%	51.22	73.20	80.69	92.05	**75.20**	**86.49**
N	123	194	145	151	**613**	**296**
Touchscreen use (minutes)						
M	8.53	18.80	25.18	44.11	**24.45**	**34.81**
(SD)	(15.54)	(36.83)	(37.46)	(47.75)	**(38.98)**	**(43.96)**
N	123	194	145	150	**612**	**295**
First scroll (months)						
M	6.33	9.05	13.46	16.62	11.91	**15.11**
(SD)	(2.11)	(2.77)	(4.85)	(6.66)	(5.93)	**(6.06)**
N	65	152	119	130	466	**249**
First video (months)						
M	6.04	8.45	13.02	16.20	11.66	**14.67**
(SD)	(2.37)	(3.54)	(5.45)	(6.92)	(6.37)	**(6.45)**
N	58	126	116	126	426	**242**
Gross motor (months) Sitting						
M	5.64	5.71	5.49	5.86	5.68	**5.67**
(SD)	(0.98)	(1.25)	(1.13)	(1.52)	(1.25)	**(1.34)**
N	120	197	149	144	610	**293**
Walking						
M	10.56	12.10	12.81	12.91	12.58	**12.86**
(SD)	(0.53)	(1.75)	(2.15)	(2.52)	(2.20)	**(2.34)**
N	9	136	150	148	443	**298**
Fine motor (months) Pincer grip						
M	6.74	8.02	8.34	8.07	7.88	**8.21**
(SD)	(1.95)	(2.06)	(2.67)	(2.78)	(2.44)	**(2.72)**
N	96	185	131	121	533	**252**
Stack blocks						
M	9.50	12.10	13.26	13.33	12.91	**13.29**
(SD)	(1.52)	(2.37)	(3.70)	(4.65)	(3.81)	**(4.17)**
N	6	87	126	113	332	**239**
Language (months) First word						
M	7.97	10.72	12.24	11.21	11.11	**11.75**
(SD)	(2.09)	(2.55)	(3.30)	(3.52)	(3.24)	**(3.44)**
N	35	151	140	126	452	**266**
Two words						
M	8.00	13.98	17.20	16.62	16.38	**16.90**
(SD)	(2.83)	(2.62)	(3.79)	(4.49)	(4.15)	**(4.17)**
N	2	44	114	124	284	**238**

To assess the association between age of first touchscreen use and age of achieving developmental milestones, three separate partial correlations were run for gross motor skills (walking), fine motor skills (stacking blocks), and language (producing two-word utterances) with age of touchscreen use, covarying for the corresponding 'early' milestone (pincer grip, sitting and first word, respectively), mother's education (a proxy for social economic status), age, and sex. Partial correlations were chosen as the retrospectively reported time of first touchscreen use and age of achieving milestones varied in the order of which occurred first, so the direction of effect cannot be inferred.

RESULTS

How Does Touchscreen Use Change From 6 To 36 Months?

In our sample, only two of the 715 respondents had no touchscreen devices in their home, average ownership being 3.73 devices per household ($SD = 1.50$, range 0–14). Among 6- to 36-month-old infants and toddlers, 9.62% of children (59/613) had their own touchscreen. When split by age (quartiles 6–11, 12–18, 19–25, and 26–36 months) ownership increased from 0% among infants aged 6–11 months through to 21.19% for 26- to 36-month-olds (see **Table 1**).

Overall, ~75% of our sample used a touchscreen, and analysis of touchscreen use by age showed that the proportion of users increased from 51.22% in 6–11 month-olds through to 92.05% by 25–36 months (see **Figure 1A**). However, within the children who did not use a touchscreen daily (i.e., ~25% of 6- to 36-month-olds) only 42.11% (64/152) reported no prior use of a touchscreen device at all. Within users, the average daily use between 6 and 36 months was 24.45 min ($SD = 38.98$, range: 0–310 min), which increased from 8.53 min per day at 6–11 months to 43.95 min at 26–36 months (see **Figure 1B**).

Retrospectively Reported Touchscreen Use and Developmental Milestones

For all the following retrospectively reported data (i.e., age of first touchscreen use and achieving developmental milestones), our analyses include only toddlers 19 months and older (i.e., a median split; $N = 366$). This is to ensure that the majority of children have had the opportunity to achieve the developmental milestones and use a touchscreen device (see **Table 1**). In these toddlers, mean reported age of first touchscreen use was 13.13 months (*SD*: 6.05), with no significant difference between age of first scrolling (mean: 15.11 months, *SD*: 6.06) and video watching (14.67, *SD*: 6.45): $t(225) = -1.17$, $p = 0.25$.

For developmental milestones, a 2 (developmental level: early, late) * 3 (domain: gross motor, fine motor, language) repeated measures ANOVA, showed a significant effect of domain [$F(2,414) = 246.15$, $p < 0.001$, $\eta_p^2 = 0.54$], with parents reporting earliest achievement for gross motor skills (estimated mean age = 9.15 months), followed by fine motor skills (estimated mean = 10.67 months) and then language (estimated mean = 14.06 months). There was also a significant effect of developmental level [$F(1,207) = 1624.79$, $p < 0.001$, $\eta_p^2 = 0.89$], with the 'early' milestones (sitting, pincer grip, and first word; estimated mean age = 8.38 months) achieved, as expected, before the 'late' milestones (walking, stacking blocks, and combining two words together; estimated mean age = 14.21 months). The developmental level by domain interaction was also significant [Greenhouse–Geisser corrected: $F(1.81,374.92) = 22.39$, $p < 0.001$, $\eta_p^2 = 0.10$], with less difference between the age of achieving the 'late' milestones compared to the 'early' milestones.

How Does Touchscreen Usage Relate to Developmental Milestones in Toddlers?

Analyzing data from toddlers between 19 and 36 months of age, we tested whether age of first touchscreen use was

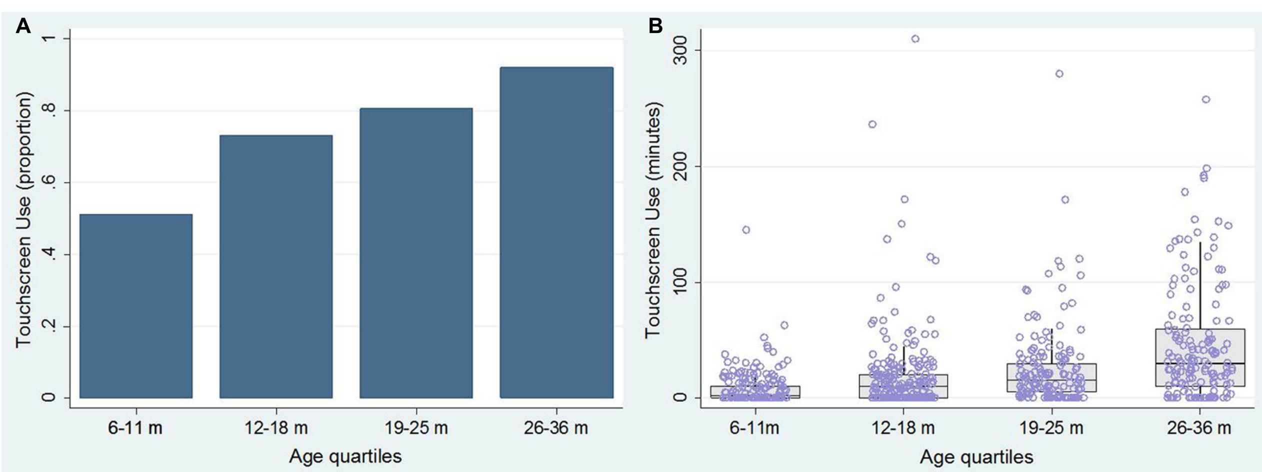

FIGURE 1 | (A) The proportion of touchscreen users for each age quartile, from 6 and 36 months. **(B)** The relationship between age and mean daily touchscreen usage (minutes).

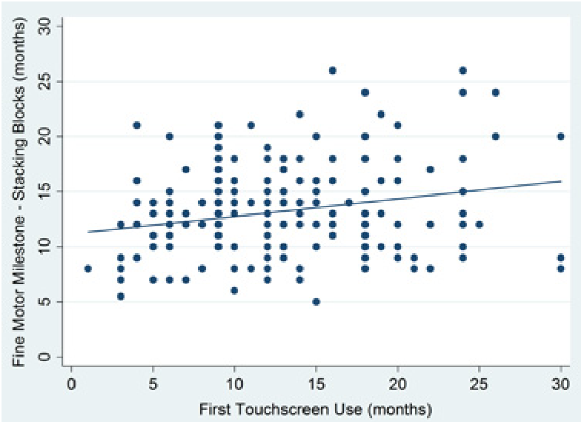

FIGURE 2 | Association between retrospectively reported age of first touchscreen use and achievement of fine motor milestone (stacking blocks).

correlated with age of achieving key developmental milestones: gross motor skills (walking), fine motor skills (stacking blocks), and language (producing two-word utterances), covarying for the corresponding 'early' milestone (pincer grip, sitting, and first word, respectively), mother's education, age, and sex. No significant associations between age of first touchscreen use and either gross motor (walking: $r = -0.08$, $p = 0.21$) or language (combining two words: $r = -0.02$, $p = 0.83$) were found. However, age of first touchscreen usage was significantly associated with the fine motor milestone stacking blocks ($r = 0.16$, $p = 0.03$) (see **Figure 2**). To test whether type of usage was important, we ran separate partial correlations for age of first active scrolling of the screen and watching videos. Age of first scrolling was significantly associated with stacking ($r = 0.16$, $p = 0.04$), controlling for previous covariates (pincer grip, mother's education, age, sex) and age of first watching videos. However, the association with age of first watching videos (controlling for scrolling) was not significant ($r = 0.04$, $p = 0.62$).

DISCUSSION

These results confirm the prevalence and rapid increase of touchscreen use over the first 3 years of life in a large UK-wide online sample. Contrary to the guidelines adopted by international parent-advisory agencies (Brown, 2011; Strasburger and Hogan, 2013) including the UK government (Public Health England, 2013), the majority (75.20%) of our 6- to 36-month-old sample of children had daily exposure to touchscreen devices, far exceeding the prescribed zero screen time for that age group. This figure is higher than reported in earlier studies examining touchscreen use up to 24 months of age (Rideout, 2013; Cristia and Seidl, 2015) but similar to the exposure reported in a recent sample from Northern Ireland (Ahearne et al., 2015) and to a low SES American sample (Kabali et al., 2015). Even within the 25% who did not report daily touchscreen use, only 42.1% reported that their child had never used a touchscreen. These results indicate that within our sample, touchscreen devices are a common part of a toddler's media environment and everyday sensory/cognitive stimulation.

The representativeness of our sample to the UK population is not known, as the recruitment was not random and participants may have volunteered due to a pre-existing interest in the topic of media and child development. The proportion of high SES families was also overrepresented in our sample with 86% with degree level education or above. However, a recent UK government survey confirms that the majority of families with somewhat older children (3- to 4-year-olds) own at least one tablet computer (65%) and use it regularly (39%; Ofcom, 2014). Our higher touchscreen exposure percentage (75.20% versus Ofcom's 39%) may be due to the fact that Ofcom does not include touchscreen smartphones within results for tablets (smartphone availability is measured separately; e.g., 41% of 5- to 15-year-olds own a smartphone; Ofcom, 2014). This is supported by a survey of 3- to 5-year-old children conducted by The National Literacy Trust which reported 72.9% access to a touchscreen device in the home including smartphones (Formby, 2014). Thus, while it does not appear that our sample is made up of families with uncharacteristically high media exposure, it is possible that there are more subtle differences in the way in which devices are being used by higher SES families. Future studies should attempt to gather a randomly selected, representative sample, or target families with low-media use to ensure representation of the full range of media environments.

One objective of this study was to address popular fears that early exposure to touchscreen devices may negatively impact toddler development (Carr, 2010; Sigman, 2012; Greenfield, 2015). In order to gather data on early development in a large online sample without the need for a long standardized questionnaire (e.g., Vineland Adaptive Behavior Scales) or observational assessment (e.g., Mullen; Mullen, 1995), we chose the age of achieving key developmental milestones: fine motor (i.e., stacking blocks), gross motor (i.e., walking), language (i.e., saying two-word utterances). However, this approach yields only single-item measures of developmental milestones. In reality of course, abilities such as walking actually develop over a period of time, from a first shaky step to confident locomotion. Future studies should collect more detailed developmental measures longitudinally, at the time they are emerging. An additional limitation is the retrospective reporting of milestones, which are subject to recall bias (Sudman and Bradburn, 1973), as well as the fact that we do not know how reliable parents are in remembering aspects of first touchscreen use. Our results did not show any evidence for negative associations between touchscreen use and developmental milestones, but there was a significant positive association between the retrospectively reported age of achieving the fine motor milestone and the age at which the child first used a touchscreen. Specifically, this relationship was only present for the child's age of first actively controlling the screen by scrolling or touching, and not for watching videos.

The average age of reaching the fine motor milestone – stacking three or more blocks – was 13.29 months ($SD = 4.17$), which is consistent with the 12–15 months age window expected for the development of block stacking (Gerber et al., 2010). The positive association suggests that infants who are actively using a touchscreen earlier are also developing earlier fine motor abilities observable with real objects. However, given that both the milestone and the age of first use are retrospectively reported and may occur in either order we cannot currently interpret the direction of this effect. It may be that infants with developmentally advanced fine motor skills are more likely to actively scroll, touch and control a touchscreen device when given the opportunity, in the same way that they will apply their newfound skills to any object placed before them. Alternately, exposure to a highly stimulating, rewarding and responsive touchscreen device prior to the onset of their advanced fine motor skills may encourage experimentation of finger and hand control which ultimately transfers to real-world objects. In order to know which of these hypothesized mechanisms is causing the effect, future studies will need to chart both touchscreen use and motor development longitudinally using more fine-grained and precise measurement.

Evidence for a relationship between active screen-based media use and fine motor skill has previously been reported in older children and adults (for review, see Green and Bavelier, 2008). Touchscreen phone use is related to increased fingertip somatosensation and associated brain activity in adults (Gindrat et al., 2015), manual dexterity and visual motor skills can be trained by videogames including specialist skills such as laparoscopic surgery (Lynch et al., 2010) and piloting an aircraft (Gopher et al., 1994). Transfer of the manual skill trained by screen-based media to the real world is often dependent on specificity of the trained virtual skill and its similarity with the real skills (Green and Bavelier, 2008). For example, a study assessing the relationship between general computer use and development in 38- to 61-month-olds found no relationship with visuomotor or gross motor development even though advantages in school readiness and cognitive development were found (Li and Atkins, 2004). To assess causality in the direction of the relationship between active touchscreen use and real world fine motor development, future studies should utilize an intervention design in which specific manual gestures/skills are encouraged in infants using a touchscreen early in development.

In terms of the assessed gross motor (walking) and language milestones (two word utterances) our analyses did not reveal any relationship – positive or negative – with the age of first using a touchscreen. The average reported age of walking onset in our toddler sample (12.86 months, $SD = 2.34$) is consistent with the expected mean walking onset (12 months; Onis, 2006; Gerber et al., 2010) as is the age of first using two-word utterances (our sample: 16.90 months, $SD = 4.17$; compared to mean onset 17–18 months: Fenson et al., 2000; Gerber et al., 2010). Our results can neither confirm nor deny the *displacement hypothesis* (Strasburger et al., 2012), which states that the time a child spends engaged with a screen limits the time they have to do other activities, leading to reduced physical activity (Sisson et al., 2010; although see Taveras et al., 2007) or face-to-face communication (Huttenlocher, 1998; Hart and Risley, 2003; Rowe, 2012; Sosa, 2016). Although, we do not have a measure of physical activity or social interaction in our sample, we do not find any evidence that touchscreen usage is displacing other forms of physical exploration that relate to the onset of walking or the social and linguistic stimulation that facilitates spoken language when other factors such as SES, sex, and age are controlled for. This absence of displacement may be, in part, because touchscreen devices are inherently portable (thus facilitating mobility), can be used collaboratively by multiple people (for an overview of pre-schooler/parent tablet co-use see Marsh et al., 2015) and are increasingly being used in parallel with other media such as TV (74% of 14- to 17-year-olds report using a smartphone whilst watching TV; Accenture, 2015). In addition, it may be that early touchscreen use impacts language and gross motor only later in development, when these skills are more advanced (e.g., vocabulary size, physical activity), rather than the early milestones assessed here.

Our findings are the first attempt to identify the impact of the recent introduction of touchscreen devices into the early environment of toddlers on development. The results of the current study provide no evidence of a negative association between toddlers' use of touchscreen devices and developmental outcomes and even suggest a positive association with fine motor development. However, our current analysis is limited by the fact that we do not have a measure of how much each child was using a touchscreen prior to reaching developmental milestones. Our only measure of the amount of usage is reported at the child's current age and we do not know how this relates to earlier usage. To examine whether the association between early touchscreen use and age of reaching developmental milestones is "dosage" dependent or varies with other usage factors (such as co-use, physical context, or type of use), future studies will need to use more reliable methods of tracking current touchscreen use such as media diaries or objective measures (e.g., device monitoring). Also, our present analysis does not report other aspects of development that may also be associated with early touchscreen use such as eyesight problems (e.g., increased myopia in children who read intensely; Ip et al., 2008), muscular and skeletal pain and problems due to excessive use (e.g., phone use in adults; Berolo et al., 2011), sleep problems (e.g., videogame use in children; Dworak et al., 2007), emotion and conduct problems (e.g., childhood TV predicting adult problems; Robertson et al., 2013), or cognitive development such as attention control and executive function (e.g., the immediate impact of fast-paced TV viewing; Lillard and Peterson, 2011). More precise lab-based assessments of these factors are required along with the detailed analysis of touchscreen usage. Future intervention studies that can control for pre-existing differences in these groups and help to address questions of causality will also be important, although the ethical issues of how to introduce a potentially negative influence into a child's environment must be addressed first (Bavelier et al., 2010). A more nuanced charting of the exact ways in which children are using the touchscreen, as well as the pedagogical and age-appropriateness of the apps (Hirsh-Pasek et al., 2015), is required. Given the inherent flexibility of these devices, not all use can be considered to have the same impact on development (Christakis, 2014). This view is supported by the differential association we find between the age of fine motor milestone achievement and touchscreen scrolling versus video watching.

Our results suggest that touchscreen use by toddlers is prevalent in the UK and only likely to increase given the increasing computational intelligence and adoption of touch as a mode of interaction by almost all household appliances, toys and even clothing (e.g., smartwatches and running gear). The intuitive nature of touchscreens for pre-linguistic children (Cristia and Seidl, 2015) means that the current recommendations for zero screen time for children under 2 years is out of line with the reality of the current home media environment of most toddlers and difficult to enforce by parents who themselves are conducting more of their lives through such devices. Parents may also be considering touchscreen devices as exempt from the "no screens" guidelines, as has previously been reported for infant and toddler use of videochat (McClure et al., 2015). Our evidence that children who scroll touchscreen devices earlier may develop fine motor control earlier is the first indication of how our current generation are adapting to their new media environment and setting the foundation for a life spent interacting with such devices. How such exposure relates to long-term development, educational achievement and impacts future society are pressing research questions facing developmental science.

AUTHOR CONTRIBUTIONS

RB: conceptualized and designed the study, analyzed the data, and wrote the paper; ISU: designed and implemented the questionnaire, processed the data, and contributed to drafts of the paper; CC: coordinated questionnaire recruitment, processed the data, and contributed to drafts of the paper; AK-S: conceptualized and designed the study and contributed to drafts of the paper; TS: conceptualized and designed the study, analyzed the data and wrote the paper.

FUNDING

The TABLET project was funded by a Philip Leverhulme Prize (PLP-2013-028) to TS. RB was supported by a Sir Henry Wellcome Postdoctoral Fellowship.

ACKNOWLEDGMENTS

We are very grateful to all the parents who took part in this online questionnaire and to the Centre for Brain and Cognitive Development, Goldsmiths Babylab, the NCT and Fundamentally Children for help with recruitment. We also thank Shaili Shah for help with data cleaning.

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Conflict of Interest Statement: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

frontiers in Psychology

MINI REVIEW
published: 18 July 2016
doi: 10.3389/fpsyg.2016.01078

Young Children Learning from Touch Screens: Taking a Wider View

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Touch screen devices such as smartphones and tablets are now ubiquitous in the lives of American children. These devices permit very young children to engage interactively in an intuitive fashion with actions as simple as touching, swiping and pinching. Yet, we know little about the role these devices play in very young children's lives or their impact on early learning and development. Here we focus on two areas in which existing research sheds some light on these issues with children under 3 years of age. The first measures *transfer of learning*, or how well children use information learned from screens to reason about events off-screen, using object retrieval and word learning tasks. The second measures the impact of interactive screens on parent-child interactions and story comprehension during reading time. More research is required to clarify the pedagogical potential and pitfalls of touch screens for infants and very young children, especially research focused on capabilities unique to touch screens and on the social and cultural contexts in which young children use them.

Keywords: touch screens, very young children

OPEN ACCESS

Edited by:
Joanne Tarasuik,
Swinburne University of Technology,
Australia

Reviewed by:
Sabine Heim,
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University of Maryland, USA

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Specialty section:
This article was submitted to Developmental Psychology, a section of the journal Frontiers in Psychology

Received: 26 April 2016
Accepted: 01 July 2016
Published: 18 July 2016

Citation:
Lovato SB and Waxman SR (2016) Young Children Learning from Touch Screens: Taking a Wider View. Front. Psychol. 7:1078. doi: 10.3389/fpsyg.2016.01078

Scene from the New York City subway, 2015: A sweet mom is riding with her 3- or 4-year-old daughter. The girl asks, "Where are the stairs? When are we going up the stairs?" Instead of following the child's lead (e.g., telling her about the stairs, looking for stairs together, explaining that stairs are at the ends of the stations because there are no stairs in the tunnels, etc.), the mom starts drilling her on the sounds of letters. "What word starts with A, what word starts with B", etc. They got to O - a hard one - and the child got frustrated. At this point, the mom handed her a tablet with a video game, and she turned to her own phone.

Episodes like this one, shared by a colleague, have become increasingly common. After all, touch screens are everywhere, and even the most devoted parent sometimes needs to turn her attention elsewhere, even if only briefly. Moreover, we know that even before their first birthdays, infants *can* learn from material presented on screens, as witnessed by their success in lab-based tasks as diverse as perceptual discrimination, pattern detection and word learning.

Observations like these – in subways and in infant labs – raise fundamental questions for the 21st century. What exactly can infants and very young children learn from the screen? On the one hand, although several 'educational' programs for infants and young children claim to teach a variety of skills, evidence-based investigations reveal that most fall far short of their mark (Zimmerman et al., 2007; Robb et al., 2009; DeLoache et al., 2010; Neuman et al., 2014). On the other hand, a review of the infancy literature reveals that infants can indeed learn a great deal from screens, including new words for objects and actions (Barr et al., 2007; Yuan and Fisher, 2009; Arunachalam and Waxman, 2010). Perhaps even more remarkable, infants as young as 18 months of age – most of whom speak only in single word utterances – can use the (few) words they do know to learn new words, even when the entire task takes place on a screen (Ferguson et al., 2014).

Our goal here is to summarize what we know about the conditions under which infants and toddlers learn from interactions with touch screens. In contrast to the growing body of research addressing this issue in preschool-aged children (see Hirsh-Pasek et al., 2015 for a review), the evidence from very young children – especially those younger than three – remains sparse. Therefore, our goal is to review two research arenas in which considerable headway with this age-group has been made, and to highlight directions for additional research with infants and children under 3 years of age.

YOUNG CHILDREN'S ACCESS TO TOUCH SCREENS

Young children's access to touch screens has increased rapidly and dramatically. In October 2015, the Pew Research Center reported that at least 83% of all 18- to 49-year-olds in the US – the age group most likely to be parents of young children – owned smartphones (Anderson, 2015). Another recent investigation focusing directly on low-income minority families from suburban Philadelphia with children ranging from 6 months to 4 years painted the same picture (Kabali et al., 2015): 83% of these families had tablets at home, 77% had smartphones, and 96.6% of the children had used these devices, many before their first birthdays. Two years earlier, the nationally representative Common Sense Media survey reported that 38% of children under 2 had used a mobile device (Rideout and Saphir, 2013). Clearly, touch screen devices are rapidly gaining a place in the lives of US families with young children.

Why the explosion now? For decades, attractive, interactive graphic interfaces have been available on home computers. But young children's access to these was limited by both their cost [with the cost of hardware, software, and home internet contributing to the "digital divide" (Norris, 2001)] and by the fine motor skills and eye-hand coordination required to manipulate a keyboard and mouse. With the advent of touch screens on less expensive devices – smartphones and tablets – these financial and developmental barriers have been reduced: By their first birthdays, most children can become adept at touching, swiping and pinching on the screen. As a result, children's access to touch screens has outpaced what we know about its effects – for better or worse – on early development.

The Gap Between Children's Touch Screen Use and What We Know about Its Developmental Consequences

Because the research on touch screen use has not kept pace with their steep rate of adoption, there is a gap in our knowledge of their developmental impact, especially in children younger than three.

Several companies have claimed that infants learn from using their devices or apps. Academic researchers, on the other hand, have been more skeptical, asking about what conditions are required to support infants' and young children's learning from screens (c.f., Richert et al., 2010; Hirsh-Pasek et al., 2015).

Recent evidence points to both the promise (e.g., Rosin, 2013) and challenges of touch screen use (e.g., Glaser, 2014; Honan, 2014). The American Academy of Pediatrics (2011) has continued to recommend that screen time be minimized for children younger than 2 years of age. Researchers from early childhood education, developmental psychology and the learning sciences have raised questions about the impact of touch screens on cognitive and social development. Other questions concern what children can (or cannot) learn from screen-based interactions.

There is no doubt that, for the most part, young children learn best from exchanges with caring adults. There is also growing evidence that children learn more from media when their caregivers are actively engaged in what is known as *joint media engagement* (Takeuchi and Stevens, 2011). Moreover, when devices, apps, and toys are noisy, they interfere with the kinds of interactions that are best-suited for language and cognitive development (Kirkorian et al., 2009; Zosh et al., 2015). Thus, when parents or caregivers are available, very young children learn best interacting with them, without the interference of noisy devices.

But how often are young children engaged with parents or caregivers while using touch screens? And what do children learn from touch screens when they use them alone, at times when parents strive to keep them occupied, amused or momentarily distracted from a source of conflict?

A review of the research with children younger than three reveals two distinct, but relatively comprehensive, lines of work. The first measures *transfer of learning*, or how well children use information learned on-screen to reason about events off-screen. The second measures learning from interactive screens on during reading time.

LEARNING FROM SCREENS: THE POWER OF INTERACTION

Transfer Tasks

The now-classic transfer task, pioneered by DeLoache (1987, 1989, 1995) and DeLoache et al. (1997) was designed to measure young children's ability to transfer information gleaned from one medium (e.g., a 3D model, picture, screen-based depiction) to the 'real world'. In the classic model room task, children first played with an experimenter in a room. Next, they accompanied the experimenter to a different location (e.g., a room with a 3D model of the life-sized room); here, the experimenter used the 3D model to demonstrate where a real toy had been hidden in the life-sized room. Finally, the child was asked to search for the real toy in the real room. To succeed, children had to transfer what they learned from one medium (e.g., the small 3D model room) to a new context (actual room). The evidence consistently revealed that transfer tasks like this are difficult for children younger than 30 months (DeLoache, 1995, 2000).

More recently, researchers have adapted this task to consider children's ability to transfer information they learned from a video screen. The results converged well with the original findings: young children had difficulty transferring information about a hidden toy's location from a video presentation to the real room. However, they readily transferred this information if it was presented to them in an interaction with an experimenter. This phenomenon is known as the *video deficit* (Troseth and DeLoache, 1998; Barr and Hayne, 1999; Schmitt and Anderson, 2002; Barr, 2010; see Anderson and Pempek, 2005 for a review).

Interestingly, children's difficulty does not seem to come from screens themselves; what seems to be key is whether they have an opportunity to engage with the screen contingently.

For example, Troseth et al. (2006) adapted the task to study the effect of social interaction on 2-year-olds' transfer ability. First, an experimenter showed the child where a toy was hidden in a room. What varied was how she showed them. Half of the children learned the toy's location by watching a closed circuit video feed as the experimenter hid the toy (video condition); the others learned by accompanying the experimenter as she hid it in the real room (live condition). Children in the live condition successfully found the toy 77% of the time. In contrast, success in the video condition plummeted to 27%.

In a second experiment, all children learned about the hiding place from video. What varied was whether the hiding information was provided in an interactive or non-interactive fashion. In the interactive video condition, cameras were placed in both rooms and the experimenter interacted with the children throughout the hiding episode. To begin, the experimenter (with whom the child was interacting via video) played with the child for 5 minutes, establishing herself as a responsive and engaged social partner. Then, she hid the toy as children continued to watch on video. In the non-interactive control condition, children watched a 5-min recorded video of the experimenter interacting with a previous participant and then watched the experimenter hide the toy. Children in the interactive video condition successfully found the hidden toy 65% of the time; those in the non-interactive video condition succeeded at a rate of only 35%. This documents that children can indeed transfer information about the hiding location from a screen, but do so best when they are engaged with the experimenter doing the hiding.

Lauricella et al. (2010) also engaged 2½ and 3-year-old children in a transfer task, this time including an interactive computer-based condition. Children were brought into a real room and introduced to three stuffed animals who were going to "play hide-and-seek". After becoming familiar with the room and the characters, children were brought to an adjacent room where they were randomly assigned to one of three conditions: (1) playing a "computer game" that permitted them to press a space bar to reveal the characters' locations on a screen, (2) watching the same game unfold on the screen without interacting with it (a previously recorded video of a researcher playing the game) or (3) seeing the characters hidden by watching events taking place in the real room through a one-way mirror. As predicted, children were very successful with the one-way mirror. But they were equally successful in the interactive, bar-pressing computer game condition. Children in these conditions surpassed those in the non-interactive computer game condition. This converges with Troseth et al. (2006)'s findings, suggesting that young children learn better from contingent than non-contingent video experience.

With increasing age, children become increasingly successful at transferring what they learn from screens to other media, such as print, or real life (Aladé et al., 2016; Huber et al., 2016). Although these studies offer encouraging news about preschoolers' ability to transfer learning from touch screens, they leave open the question of how well younger children fare.

Word Learning Tasks

Other researchers have considered children's ability to transfer information from screens in a different way, focusing on how successfully children learn new words from various media sources. Skype and other video chat programs are of great interest, especially since young children use them to stay in touch with distant family members. Roseberry et al. (2014) asked whether 24- to 30-month-olds could learn the meaning of new words – they focused on verbs – in three conditions: live interaction, video interaction, or *yoked* video (pre-recorded). Children were taught four novel verbs (e.g., "meeping" for a novel turning action). An experimenter performed the action while using the novel verb in complete sentences (e.g., "I'm *meeping* this toy") in each of the three conditions. In the live interaction and video interaction conditions, children went through a warm-up period in which the experimenter addressed them by name and played with them. Children in the yoked video condition watched a previously recorded video of the experimenter as she interacted with another child via video chat. Next, children were shown clips from *Sesame Beginnings* on a split screen. On one half of the screen, the characters performed the actions matching the novel verb on which children had been trained; on the other half, they performed a non-matching action. While they watched these videos, children heard, "Where is *meeping*? Can you find *meeping*?" Children's looking and gesturing to the two screens was recorded.

Children in the live and video interaction conditions looked at the matching action significantly longer than the non-matching action. There was no significant difference between them. Children trained in the yoked video condition, however, did not appear to learn. This lends additional support to the view that interaction is key, not whether the training occurred live or on a screen.

Additional converging evidence comes from Kirkorian et al. (2016), who measured 2-year-olds' word learning from tablets. All children watched a tablet presentation in which an actress introduced four objects, hidden in a row of boxes. In the non-contingent condition, children watched as the experimenter continuously retrieved each object from its box and named it. In the general contingent condition, the video paused after each object was retrieved; only when children touched the screen did the story advance to the next segment (analogous to Lauricella et al., 2010's spacebar interaction). In the specific contingent condition, children touched each individual box on the screen to see the object it contained and hear its name. Children first completed a set of training trials with four familiar animal figurines. Then, in the testing phase, they viewed four novel objects; only the last object was named (e.g., "a toma"). Next, children were asked to select the "toma" from a set of four objects placed before them. Interestingly, 30- to 36-month-olds successfully learned the word in all three conditions, but 24- to 30-month-olds were successful only in the specific contingent condition. This suggests that 24-month-olds can learn from a tablet screen, but only when they are engaged in specific contingent interaction.

In sum, young children are more successful in learning words and locations of hidden toys from screens if they are involved in *specific contingent interactions*, as compared to passively watching events unfold (Lauricella et al., 2010; Kirkorian et al., 2016).

STORY TIME AND SCREENS: THE POWER OF SOCIAL INTERACTION

Research focusing on learning during story time has also identified the effects of screens and social interaction. This line of work builds on previous evidence of the advantages of *dialogic reading*, a reading style in which caregivers prompt children with questions to help engage them in the story (Whitehurst et al., 1994). Thus, current researchers tend to hold constant the child's engagement with an adult, and to vary whether the story is presented in a book or an electronic device (Parish-Morris et al., 2013; Krcmar and Cingel, 2014; Lauricella et al., 2014).

Krcmar and Cingel (2014) recorded parent-child pairs as they read two similar stories, one presented as a traditional book and the other on an iPad screen (a still version, with no animation or interactive features). The children ranged in age from 24 to 52.5 months. Children's comprehension from the book was significantly higher than from the iPad. Moreover, parents and children alike spontaneously offered more story-related comments and asked more story-related questions when reading the paper book. Intriguingly, parents (but not children) made more distracted (not story-related) comments in the iPad book condition. What remained unanswered was whether this advantage for books over screens at story time would change over the preschool years.

Evidence from Lauricella et al. (2014) suggests that the book advantage fades with age and experience. These researchers recorded 4-year-old children and their parents, reading both a paper book and a screen-based book. This time, the screen book had interactive features. Children's comprehension was comparable from books and screens. There was also a hint that parents may have been slightly more engaged in the computer version, where the interactive features (e.g., clicking a character to find out more about her) were integral to the story. Apparently, then by 4 years of age, children comprehend well from books and screens, and interactive features may boost their screen learning.

Parish-Morris et al. (2013) went one step further, using 'electronic console books' to tease apart the contributions of screens, *per se*, and their interactive features. Electronic console (EC) books are hybrids of traditional books and touch screens: A paper book and a matching cartridge are inserted into a console, enabling sound and interactive features that can be activated by touch. Interestingly, 96% percent of the families in their sample reported having EC books at home. In the first study, Parish-Morris et al. (2013) analyzed dialogic interactions between parents and their children (either 3 or 5 years of age). Each parent-child dyad was randomly assigned to either the traditional book condition, the EC book condition or a control condition involving the EC book but with the interactive features turned off. Results revealed that parents in the EC condition provided less language related to the story and more language directed at children's behavior (e.g., asking children to stop pressing buttons) than in the other two conditions.

In the next study, Parish-Morris et al. (2013) compared 3- and 5-year-old children's comprehension in a new group of parent-child pairs. Dyads were assigned randomly to either a traditional book or EC book (including all the interactive features) condition. Although 5-year-olds performed at ceiling after reading books in traditional and EC formats, 3-year-olds comprehended significantly more in the traditional book than the interactive, EC book condition. What remains unclear is whether this developmental effect reflects differences in the format itself or differences in parents' comments when reading in the two formats, and how children younger than 3 years of age fare with interactive vs traditional book formats.

REMAINING QUESTIONS

Many questions remain about how, and how well, infants and toddlers learn from touch screens. Here, we highlight three broad areas for future research.

(1) What Apps Are Best for Very Young Children? And for What Purpose?

First, we need to understand the potential of touch screen devices to support learning in very young children, taking into account not only their abilities to engage with the screen, but also their engagement with unique features of modern touch screen devices such as localized content, cameras, and speech recognition.

Throughout history, when a new medium is introduced, it first tends to be used in the same ways as previous media. This happened with film: the very first films were moving photographs, each capturing a moment. Later, when it became possible to make longer movies, films simply portrayed live plays, with a single camera set in front of the theater stage. It took a long time before multiple cameras were used, with different angles, close-ups, etc. The same is true for television: the first TV shows were essentially radio shows in which one could see the 'talking heads'. Also, the first news websites looked just like printed newspapers. It took some time for producers to realize how to take full advantage of the new medium. The same is likely true for tablets and smartphones: we have only scratched the surface of their capabilities.

It is currently unclear whether the perils and promise of touch screens for young children are related to something inherent about screen-learning itself or to lingering use of design choices adapted from older technologies. For example, if an electronic book is distracting, and therefore less effective than a paper book, how might distraction be ameliorated in new implementations? In their comprehensive review, Hirsh-Pasek et al. (2015) highlight the importance of social interaction, especially for the youngest children. More specifically, they argue for the value of promoting "minds-on," active interactions that facilitate children's ability to integrate new ideas with their existing knowledge. As technology continues to evolve and new designs become possible, ideas like these will serve as a blueprint.

After all, mobile devices with touch screens can offer experiences that weren't possible before. Touch screens now permit a child to see herself in a story, allow parents to record stories or to describe photos in a family album, etc. More research is needed to understand how the features that are unique to touch screen technology can best be used to advance learning in young children.

(2) When Do Infants and Very Young Children Use Touch Screens?

Second, a more careful look at the *contexts* in which parents and children use touch screens is needed. Return for a moment to the little girl and her mother on the New York subway. We all have seen caregivers using smartphones or tablets to entertain, and perhaps pacify, young children. What remains unknown is where, when, with whom and how young children use touch screens.

In a national survey, Wartella et al. (2013) provide insights into how parents use touch screen with their children. Among parents of children ranging from 0 to 8 years, 14% reported that they were "very likely" to give their child a mobile device to keep them occupied at a restaurant; 24% said they were "somewhat likely" to do so. Their reported use of mobile devices at home was lower.

If parents largely offer smartphones and tablets to their infants and young children to entertain them while they are otherwise engaged, then it would be advantageous to figure out (a) what young children actually tend to do with the devices, and (b) what kinds of apps would be most beneficial in such contexts. If parents are using the devices with their children some of the time, it is important to understand how to support, not get in the way, of parent-child interactions. For example, apps can be programmed to run differently when an adult is engaged with the child (i.e., by letting the adult, rather than the app, do the talking) than when the child is alone. As touch screen technology and the corresponding content evolves, more research is needed not only on current usage patterns, but on methodologies that track children's use.

Smartphones and tablets can be programmed to track incredible amounts of data – provided, of course, that adequate privacy protections or consent are in place – including how long an app was used, every touch on the screen and even the location of the child during the interaction. This data would reveal how children from 0 to 3 years of age use touch screens and how (much) they learn from them.

It will also be important to identify what kinds of learning opportunities children miss out on when they are occupied with touch screens, rather than engaging with others and observing social interactions. Turkle (2012) offers considerable food for thought along these lines, articulating how our nation's increasing engagement with digital devices come at the expense of the learning and social connections that arise naturally from real-time conversation and engagement with others. A pressing concern is how infants' and young children's burgeoning access to touch screens affects their ability to communicate with and relate to others.

(3) How Does Touch Screen Adoption and Use Vary Across Cultural Communities?

Third, entirely absent from the literature thus far is a careful consideration of the role of culture. How do families from different cultural communities incorporate mobile devices into the routines of infants and very young children? Are parents hoping devices will bolster skills they don't feel prepared to teach themselves (such as a second language, in the case of immigrant families)? What are best practices for parents and educators of children from all of our nation's diverse communities?

We look forward to new research that will illuminate both the promise and perils of touch screens in early development.

AUTHOR CONTRIBUTIONS

SL and SW contributed to the critical analysis of the literature, drafting, revising, and approving the final manuscript.

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Conflict of Interest Statement: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

frontiers in Psychology

ORIGINAL RESEARCH
published: 07 July 2016
doi: 10.3389/fpsyg.2016.01021

U Can Touch This: How Tablets Can Be Used to Study Cognitive Development

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Edited by:
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Specialty section:
This article was submitted to Developmental Psychology, a section of the journal Frontiers in Psychology

Received: 23 May 2016
Accepted: 21 June 2016
Published: 07 July 2016

Citation:
Semmelmann K, Nordt M, Sommer K, Röhnke R, Mount L, Prüfer H, Terwiel S, Meissner TW, Koldewyn K and Weigelt S (2016) U Can Touch This: How Tablets Can Be Used to Study Cognitive Development. Front. Psychol. 7:1021. doi: 10.3389/fpsyg.2016.01021

New technological devices, particularly those with touch screens, have become virtually omnipresent over the last decade. Practically from birth, children are now surrounded by smart phones and tablets. Despite being our constant companions, little is known about whether these tools can be used not only for entertainment, but also to collect reliable scientific data. Tablets may prove particularly useful for collecting behavioral data from those children (1–10 years), who are, for the most part, too old for studies based on looking times and too young for classical psychophysical testing. Here, we analyzed data from six studies that utilized touch screen tablets to deliver experimental paradigms in developmental psychology. In studies 1 and 2, we employed a simple sorting and recall task with children from the ages of 2–8. Study 3 (ages 9 and 10) extended these tasks by increasing the difficulty of the stimuli and adding a staircase-based perception task. A visual search paradigm was used in study 4 (ages 2–5), while 1- to 3-year-olds were presented with an extinction learning task in study 5. In study 6, we used a simple visuo-spatial paradigm to obtain more details about the distribution of reaction times on touch screens over all ages. We collected data from adult participants in each study as well, for comparison purposes. We analyzed these data sets in regard to four metrics: self-reported tablet usage, completeness of data, accuracy of responses and response times. In sum, we found that children from the age of two onwards are very capable of interacting with tablets, are able to understand the respective tasks and are able to use tablets to register their answers accordingly. Results from all studies reiterated the advantages of data collection through tablets: ease of use, high portability, low-cost, and high levels of engagement for children. We illustrate the great potential of conducting psychological studies in young children using tablets, and also discuss both methodological challenges and their potential solutions.

Keywords: tablet, touch screen, developmental psychology, methodology, children, memory, perception, recognition

INTRODUCTION

Nowadays, new technologies accompany us nearly every second of our life. This is especially true of devices with touch screens, like smartphones or tablets, which have become our almost constant companions. This is not just the case for adults. Children too are not only fascinated by these devices, but are also able to easily access them due to the absence of any additional input requirements like mice or keyboards. For example, Cristia and Seidl (2015) report that about a third of children aged 5–11 months already have at least a monthly interaction with touch screens. This contact rises to almost 90% by the age of 3. Children this young can already tap (71%), flick (68%), drag (41%), and more. Indeed, Abdul Aziz et al. (2013) found that 2-year-olds can already tap and drag, while 3-year-olds also rotate and flick, and 4-year-olds can perform seven common touch screen gestures without difficulty. While these investigations focused on the general ability to interact with a touch screen, several areas of science have approached the use of touch screen tablets through more specific paradigms. In education, for example, Couse and Chen (2010) argue that interaction with tablets in the class room is viable: Children between the age of 3 and 6 are found to be curious about the new technology and "persisted without frustration" when learning to use them. Importantly, this active interest actually seems to carry over to increased learning. Neumann (2014), in a study investigating the effects of tablet use on literacy knowledge, found that at ages between 3 and 5, children showed improved letter sound and name writing skills when they had greater access to tablets. Having access to tablets was also found to be advantageous in a study by Hourcade et al. (2012) about the pro-social behavior in children with autism spectrum disorders (ASD). They provided children with ASD (age 5–14) with touch-screen-based applications and found that the mere use of this technology improved collaboration between children and provided a novel way to children with ASD to express their feelings. In a more general approach, Sobel et al. (2016) developed a tablet-based application that focused on promoting the inclusion of children with mixed abilities when playing with children without impairments. In short, they found that technology-forced interaction could improve cooperation between children pairs with and without disabilities. To help these advances, standardized testing (e.g., Luciana et al., 1999) is already employed by touch-screen-mediated technology since several years. Generally speaking, both parents (e.g., Neumann, 2014) and scientists (e.g., Christakis, 2014) seem to have a positive attitude toward touch screen technology and its effects on cognitive development and/or its use as a mediator of knowledge.

In developmental psychology, tablet-based experimentation has the potential to solve the challenge of the methodological gap between video-based preferential looking tasks and standard psychophysical experimentation. The former is often used with infants and toddlers (e.g., Delle et al., 2015), as they lack the necessary motor development to produce reliable, distinct and measurable physical responses to stimuli. But as these are purely passive tasks, young children from the age of 2 upwards are quickly bored when presented with the same paradigm over and over (e.g., multiple trials of the same task). On the other hand, children this young generally lack the necessary concentration and persistence to complete classical psychophysical paradigms, which have many trials and are often monotonous and repetitive. In many areas of developmental research, scientists have resorted to creative interactive experiments, for example using role plays (Warneken and Tomasello, 2008) or physical stimuli (Meltzoff, 1988). Unfortunately, such paradigms are often hard to quantify and difficult to conduct on a larger scale because of their labor-intensive nature during both data collection and analysis.

Furthermore, when investigating questions in the field of perceptual development through computerized measures one issue, that is prevalent in younger children, is response matching. By giving an answer through a mouse click or pressing a key to a stimulus on the screen, young participants often feel the need to physically look toward the input device and back onto the presentation device to match their response with the correct position on the monitor, what makes the process rife with errors. Additionally, these approaches require participants to be generally able to operate a computer and its input devices, which is of particular difficulty in children below the age of 5. Here, some studies test children (e.g., Suhrke et al., 2015) in such a way, that the children only indicate their answers (e.g., by saying it out loud), while the experimenter gives the physical response. Obviously, this procedure is prone to errors due to miscommunication between experimenter and participant, might introduce severe experimenter's bias and lacks the possibility to record reaction times. Furthermore, work stations with equipment (monitor, mouse, keyboard, loudspeakers) are of a very stationary nature.

Touch screen tablets could help with these issues. On the one hand, the computerized, digital data conduction would allow for a more neutral, bias-free recording and easier analyses compared to role plays or physical constructs. But more importantly, due to the employment of tablets as paradigm mediators, large-scale parallel data acquisition could be realized by having young participants directly interact with the experiments, compared to the need for lengthy one-on-one sittings with current methods. Additionally, in areas, in which education is combined with a high number of children, such as museums, kindergartens, and schools, data conduction could be swift, comfortable, and rewarding for both parties.

To investigate their potential, Frank et al. (2016) very recently conducted a first study to test the general viability of tablets in developmental cognitive research in children (age 1–4). They compared three methods of measuring response during a word-recognition paradigm: presentation on a web-technology-based tablet, a storybook method and an eye-tracking paradigm. Their results showed the tablet to be on par or even favorable to the other methods in reliability, performance and sensitivity of reaction times, thus arguing in favor of adopting tablet-based paradigms as a viable new research method.

Taken together, initial evidence suggests utilizing tablets might help to fill the aforementioned methodological gap in developmental research: their high accessibility, ease of use, relatively low cost and accurate, digital measurement abilities provide everything needed to successfully conduct cognitive experiments with young children. Additionally, Frank et al. pointed out that tablets both increase the accessibility of special populations and remove some sources of experimenter bias through computerized stimulus presentation. Thus, utilizing tablets holds promise for allowing researchers to not only collect larger data sets more quickly but also to refine currently established methods. Here, we test the viability of using touch screen tablets in the study of cognitive development. We aim to identify potential limits regarding necessary motor skills and/or the maximal complexity and duration a psychological research paradigm may have for children in particular age groups when the experiments are mediated through a tablet.

In this study we analyzed six data sets, collected through independent tablet-based cognitive experiments conducted with adults as well as children between the ages of 1 and 10 years (see **Table 1** for an overview). Data sets were acquired through a variety of perception, learning, and memory tasks commonly used in adult cognitive psychology research, including sorting tasks, 2-alternative forced choice (2AFC) memory tasks, 2AFC-perception tasks, a visual search task, an extinction learning paradigm and a task for assessing spatio-temporal accuracy. Each study consisted of both a sample of adults and a sample of children. While the age of the children was dependent on the task, adults were aged between 18 and 37 in all studies. Briefly, the first two studies consisted of a two-option sorting task followed by a memory task. In both studies, stimuli had to be categorized in the first step before being recognized in a subsequent 2AFC recall task (shorthand: Sort Recall). In general, tasks in the field of perceptual development are designed as 2AFC tests as they allow for a clear differentiation between the intended responses, even in a young age. The studies differed in their level of difficulty; the first was easier (designed for children aged 2–5) while the second used more difficult stimuli (designed for children age 4–8). The third study extended the same sort of paradigm by adding bodies to the car and face stimuli included in studies 1 and 2. The study also employed an additional task, a set of staircase-based 2AFC perception tasks using the same types of stimuli as were presented in the memory task (shorthand: Sort Recall Perception). These two modifications increased the difficulty of the paradigm quite a bit (designed for children aged 9–10). The fourth study (shorthand: Visual Search) was a viewpoint-dependent visual search task with faces and cars as targets among object distractors arranged in a 3 × 3 grid, designed for children aged 2–5 years. The fifth study (shorthand: Extinction Learning) investigated an extinction learning paradigm in 1- to 3-year-old children. Here, some of the upwards flying balloons were only "poppable" in the learning and renewal phases (indicated through colors), while the rest were poppable throughout the whole experiment. The sixth study consisted of a spatio-temporal accuracy measurement (shorthand: Visuo Spatial RT) to obtain a baseline measurement of spatio-temporal abilities that could be used to "correct" response times across all experiments (i.e., are 3-year-olds slower than 5-year-olds when spatio-temporal skills are taken into account?). Here, the stimulus differed across trials in position and size and participants had to react as quickly as possible by touching it on the screen. This data was collected from the same participants as those in studies 3, 4, and 5; thus, this data set included children aged between 1 and 10 as well as data from the adult participants from studies 1, 3, 4, and 5.

To assess how well children can interact with tablet-based paradigms from cognitive psychology, we analyzed each study using four metrics: Usage, completeness, accuracy, and response time. This step-wise approach allowed us to analyze more finely-grained information with each subsequent metric. First, we used a simple questionnaire item to assess the prevalence of tablet use in participants, thereby allowing us to measure how tablet familiarity might change across different age-groups. Second, we checked how much of each experiment was completed by our participants. By gathering this metric, we assessed at which age children had the necessary motor skills to complete the task, as well as by which age children had the necessary motivation and endurance to complete all the trials included. If children of a particular age tended to quit an experiment early, we can infer that the experiment needs to be shorter or more entertaining to adequately engage that age group. Additionally, if there were very low rates of completion at specific ages, the complexity of the task—either on a cognitive or motor level—might be too high for use with children at that age. Cognitive requirements were further investigated through the third metric, accuracy. In this next step, data sets were checked for a high amount of error, independent of task-specific questions. Obviously, an interaction of accuracy and age is expected, as the studies in question all target age ranges during which the respective cognitive traits are thought to be developing. Despite this, performance in any age group should not be at either chance or ceiling level. Chance or ceiling performance in any group demonstrates a

TABLE 1 | Overview over all studies.

	study name / tasks	Response	Stimuli	Age Range	Duration
1	Sort Recall easy	drag and drop	faces, cars	2–5 years, adults	15 min
2	Sort Recall difficult	drag and drop	faces, cars	4–8 years, adults	20 min
3	Sort Recall Perception	drag and drop	faces, cars, bodies	9–10 years, adults	35 min
4	Visual Search	tap	faces and cars among objects	2–5 years, adults	15 min
5	Extinction Learning	tap	moving balloons	1–3 years, adults	5 min
6	Visuo Spatial RT	tap	static green frog	1–5 years, 9–10 years, adults	2 min

The table lists the studies we analyzed in this work along with basic details about each. Details for each study can be found in the methods section.

difficulty that is too high or low for a certain age. At chance levels, participants might have resorted to guessing, while no task-specific effects can be found when ceiling results are present. Lastly, we analyzed the data with regard to reaction times to identify potential age-dependent increases in speed. Thereby we were able to complement previous analyses and infer potential limitations when designing further psychophysical experiments on touch screen tablets.

Additionally, by comparing the results of each metric subsequently to adult data, we will be able to identify potential age thresholds, at which children data compares to adults. Identifying these developmental differences allows employing a guideline at which age experimental paradigms are viable, either by providing a difference in accuracy or by having comparable reaction times. Taken together, this study aspires to establish a first basis of the kinds of paradigms and experimental parameters which can be successfully conducted through tablet experimentation in developmental psychology.

METHODS

Participants

Participants were mainly recruited through visits to day care centers, kindergartens and schools in the Rhein-Ruhr area in Germany and at the Ruhr-Universität Bochum with regard to adult participants. Each participant and/or his legal guardian signed a consent form before participating. Adult participants participated out of good will or were rewarded with course credit, while children were allowed to choose from a variety of small toys after participation, regardless of completion of the experiments. Ethical approval was obtained from the local ethics board for each study.

In study 1 (Sort Recall easy), one participant was removed from the analysis due to technical issues, yielding 93 data sets. Of those, 79 participants were children in the age range of 2–5 (M = 3.43, SD = 1.15). Across these data sets, four single answers were corrected where the participant very clearly indicated that (s)he intended to choose a different stimulus after his/her decision, thereby changing three answers from "error" to "correct" and one the other way around. To prevent this issue, the arrangement of the task was changed in later studies (see 0 for details). The 14 adult participants were on average 21.21 (SD = 2.42, range = 19–28) years old. In study 2 (Sort Recall difficult) we had to exclude two of 77 participants due to technical issues, yielding 75 usable data sets. The mean age of the remaining 65 young participants was 5.88 (SD = 1.39, range = 2–8 years), while those of the 10 adults was 21.6 (range = 19–24 years, SD = 1.71). Study 3 (Sort Recall Perception) consisted of 36 participants, where 20 where in the range of 9–10 years (M = 9.65, SD = 0.49) and 16 were adults in the range of 19–30 years (M = 22.81, SD = 3.45). Of 107 data sets in study 4 (Visual Search), two had to be excluded due to visual impairment of the participants and an additional two due to missing questionnaire data. The remaining 103 participants consisted of 86 2- to 5-year-old children (M = 3.8, SD = 0.97) and 17 adults in the range from 20 to 37 years (M = 24.12, SD = 4.39). In study 5 (ExctinctionLearning), two of 64 participants were excluded because of technical issues, thus we were able to analyze 62 data sets. Of those, 46 children from 1 to 3 years participated (M = 1.76, SD = 0.67) along with 16 adults in the range of 18–30 years (M = 23, SD = 3.33). Participants of study 6 (Visuo Spatial RT) consisted of adult participants of studies 1, as well as all participants from studies 3, 4, and 5, a total of 217 data sets. Of those, seven participants had to be excluded due to technical issues, while one was excluded as there was no age given on the participation form. The remaining 209 participants were divided in 150 children from 1 to 10 years (M = 4.05, SD = 2.52) and 59 adults in the age range of 18–37 years (M = 22.32, SD = 3.47). Some adult participants took part in multiple studies, but were never shown the same stimulus material more than once. For details on the age distribution for each study, please refer to **Table 2**.

Hardware and Software

Studies 1, 2, and 3 used an Acer Iconia W510 tablet with a 10.1 inch screen, while studies 4 and 5 used an ASUS Transformer Book T300FA with a 12 inch screen (resolutions: 1366 × 768 px). Study 6 was conducted using both. With regard to the operating system, studies 1 (children data) and 2 (all data) ran on Windows 8, while all other studies ran on Windows 10. Due to the ease of implementation, we used web technology to show our stimuli and record the data. To remove the reliance on an internet connection and minimize data security concerns, we installed a local webserver. Each tablet had XAMPP 3.2 installed and ran PHP 5 on Apache 2.4. The front-end was mediated through Google Chrome and JavaScript aided by jQuery 2.1, jQuery mobile 1.4, and jQuery UI 1.10. The experiments were

TABLE 2 | Summary of participants.

	1	2	3	4	5	6	7	8	9	10	Adult	Σ
Study 1 (Sort Recall easy)		24	15	22	18						14	93
Study 2 (Sort Recall difficult)				14	14	13	14	10			10	75
Study 3 (Sort Recall Perception)									7	13	16	36
Study 4 (Visual Search)		9	23	30	24						17	103
Study 5 (Extinction Learning)	17	23	6								16	62
Study 6 (Visuo Spatial RT)	15	27	32	30	26				7	13	59	209

A list of the number of participants over all studies, presented per age.

programmed in HTML5/JavaScript and presented full-screen. To increase the sensitivity of touch screens for very young children, all tablets were adjusted to have a higher sampling rate and lower sampling latency of touch events through a registry edit (decrease of parameters Latency and SampleTime from 8 to 4). Additionally, to minimize accidental resizing or navigation, we disabled some of Chrome's gesture features ("Overscroll history navigation" and "Enable Pinch").

Stimuli and Design

Study 1: Sort Recall Easy

The first study employed a two-option sorting task followed by a 2AFC memory task to examine the development of facial recognition in children (e.g., Weigelt et al., 2014). In the first phase, participants tapped a stack of cards on the left side of the screen to reveal a stimulus. Following a 3000 ms delay, a small finger icon appeared to indicate the ability to categorize the card. Participants categorized the image through dragging and dropping the picture on the appropriate stack on the right side of the screen (see **Figure 1**, left). After all stimuli had been sorted, the memory task started. During the memory phase, participants revealed two stimuli on the left side of the screen (see **Figure 1**, right). After a 3000 ms delay, an image of a candy appeared that was also draggable. Participants were instructed to drag the candy to the image they had seen before. Each sorted and remembered image was followed by a short applause sound, regardless of the correctness of the decision. In total, three blocks were performed. The first block was a training block with four trials using dog and cat faces as stimuli, followed by a block of six faces of children (male/female), then a block of six cars (open/closed top). Within blocks, images were presented in a randomly selected order. The total duration of the experiment was ∼15 min. Each image was 300 × 300 pixels and grayscaled. To better differentiate between the cognitive tasks of categorization and memory, analyses will be performed on each task separately. All images were taken from the Internet and modified to fit the experimental design.

Study 2: Sort Recall Difficult

The second study was an extension of Sort Recall easy, but investigated the influence of paraphernalia on facial recognition (e.g., Bulf et al., 2013). We changed the arrangement of the interact-able objects by moving one stack of cards to the left and one to the right side, while presenting the pictures to be sorted in the sorting task and the candy in the recall task in the middle of the screen (see **Figure 2**). This change was intended to reduce the possibility of accidentally misplacements, a scenario that is much more likely when objects are dragged in the same direction for both categories (as noted in the participants section). This new set-up also more equally distributes stimuli over the whole screen and allows for a clearer differentiation of the intended motor act as participants must decide to move toward either the right or left side of the screen. The stimulus set of study 2 contained full-color adult faces combined with added paraphernalia (hats and glasses). While the sorting task was equivalent to study 1, the memory task therefore allowed differentiating between five possible changes for the stimulus between sorting and recall: No paraphernalia, constant paraphernalia, removal of paraphernalia, added paraphernalia, and change of paraphernalia (for an exemplary trial, see **Figure 2**). The training block at the start of the task consisted of one trial that covered each of these five possibilities. The training block preceded two experimental blocks with 10 trials each. In total, the experiment took about 20 min. The modification of stimuli between sorting and recall phase increased the overall difficulty of study 2 compared to study 1, thus we increased the age range of child participants to 4–8 years. Each of the 40 faces (20 targets, 20 distractors, gender equiprobable) was taken from the Glasgow Unfamiliar Face Database (Burton et al., 2010), while hats and glasses were

FIGURE 1 | Design of study 1 (Sort Recall easy). On the left, an example of a sorting trial (phase 1) can be seen. The image had to be dragged to the right side onto one of two available categories. On the right, an example of the recall task can be seen. Participants were instructed to drag the candy to the stimulus they recognized ("Which one have you seen before?").

FIGURE 2 | Example trial from study 2 (Sort Recall difficult). On the left, the sorting stage is shown. Each face image had to be dragged to the corresponding category on either the left or right side of the screen to clearly differentiate between the intended motor action. Subsequently, as can be seen on the right, the candy had to be dragged to the already seen face.

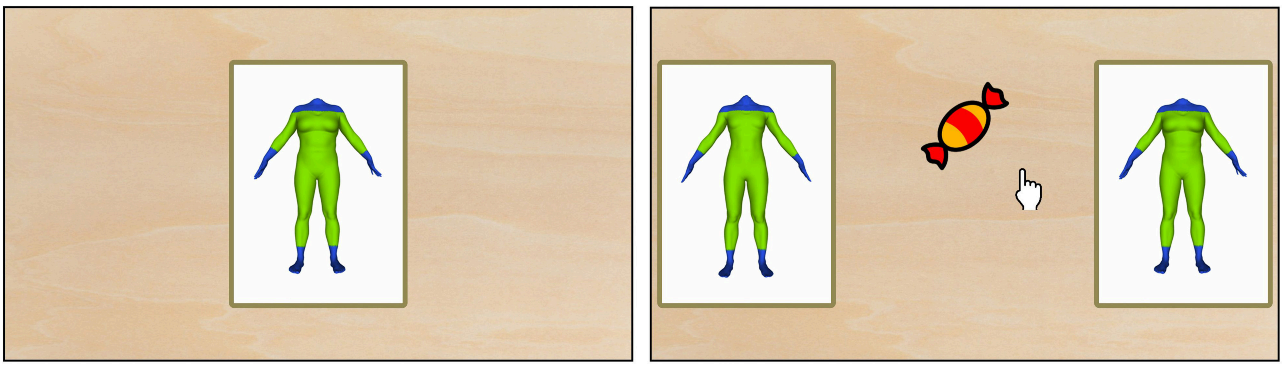

FIGURE 3 | Example perception task trial from study 3 (Sort Recall Perception). First, a stimulus was shown (left). Then, the participant was asked to drag the candy to the stimulus s(he) had seen immediately before. Each correct answer increased the similarity between target and distractor by 5%, while wrong answers decreased the similarity by 15%.

taken from various places of the Internet and adjusted to fit our needs.

Study 3: Sort Recall Perception

Extending the two previous studies, study 3 (Sort Recall Perception) covered two social and one Non-social stimuli types (faces of children, cars, bodies of adults; see Weigelt et al., 2014) and added a staircase-based 2AFC perception task. In the memory tasks, the same design and procedure as in study 2 was used but with different stimuli, shortening the delay to 1000 ms and removing the applause after each trial. The sizes of images were adjusted to better fit their natural proportions, i.e., cars being horizontally rectangular, bodies vertically rectangular and face images kept square. Bodies were clothed in skin-tight "super-hero" outfits, presented from the neck down and colored in bright green and blue to be more appealing to children (**Figure 3**). The perception task started with a centrally presented stimulus, followed by a 1500 ms delay and the subsequent presentation of two stimuli. The participant had to drag the candy to the item s(he) had seen immediately before. Each correct answer moved the distractor morph toward the target image, which was kept at 95% of the original stimulus and 5% of the distractor stimulus. Two staircases worked in a 1-up 3-down way in parallel by in-/decreasing the morphing between the two stimuli by 5% per step, thus increasing the similarity by 5% per correct and decreasing the similarity by 15% for each wrong answer. Each staircase ran until eight reversals were detected, where one reversal was defined as a wrong answer. Until the first reversal, errors in the first 25% did not result in a reversal. A minimum of 5% difference between target and distractor stimulus was enforced and trying to surpass that threshold through a correct answer was counted as a Non-error reversal, while keeping the stimulus values the same. Taken together, the three tasks took about 35 min to complete. Due to the large difference in task requirements, we split this study into its parts (sorting, memory, perception) and analyzed them accordingly. Due to much higher difficulty of the stimuli, especially in the perception task, only children from the age of 9–10 years and adults were tested. Faces were taken from the Dartmouth Database of Children's Faces (Dalrymple et al., 2013), body stimuli are 3 d mesh

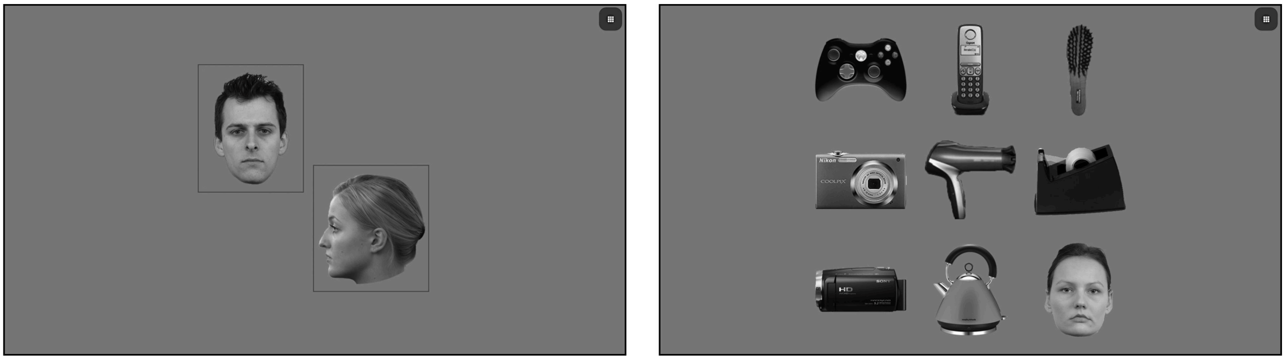

FIGURE 4 | Design of study 4 (Visual Search). At the start of each block, the target stimulus type is shown in 2 viewpoints, as can be seen on the left. Each trial consisted of an array of images containing one image from the same category (in this case faces) along with eight distractors in a grid. Participants were instructed to find and tap the target as quickly as possible.

models created from full-body scans of adults (purchased from www.bodylabs.com) and cars were taken from various websites from the Internet.

Study 4: Visual Search

Study 4 employed a visual search task with children from the age of 2–5 years (similar to Di Giorgio et al., 2012). Each block consisted of 10 trials and started with an image representative of the target type for that block, which were either faces or cars (see **Figure 4**, left) and ended with an applause sound. Each trial within the block started with a placeholder image that had to be tapped to reveal the test array. The target stimulus was presented at a random location in a 3 × 3 grid with eight distractors (see **Figure 4**, right). Upon tap on any of the images, the screen went blank for an ITI of 1000 ms before the next trial started. Two training blocks (three face trials and two car trials) preceded eight blocks of experimental trials. Each presented image was 250 × 250 px and randomly selected out of 720 possible items. In total, 40 faces (20 male, 20 female), 40 images of cars and 640 distractor images of various items roughly similar in size to the faces were used. Half of the target images were exhibited from the front while the other half were viewed from the side. Face images with a neutral facial expression were taken from the Radboud Faces Database (Langner et al., 2010), from the Karolinska Directed Emotional Faces database (Lundqvist et al., 1998) and from the Aging Mind database (Minear and Park, 2004). Photographs of cars and distractors were taken from the Internet and modified to fit our purpose. The whole task took about 15 min to complete, while after each block the participant was asked whether (s)he wanted to "continue playing the game."

Study 5: Extinction Learning

In study 5 an extinction learning paradigm consisting of three phases was performed (see Happaney and Zelazo, 2004) with children between the age of 1 and 3 years as well as with adults. In the first phase (learning), balloons of two colors ascended from the bottom of the screen to the top (**Figure 5**). Upon any of the balloons was tapped, the balloon popped and an accompanying sound was played. During the learning phase, all balloons (in two colors) were poppable. In the second phase (extinction), however, balloons were shown against a different background color (gray/blue), and only balloons of one color were poppable. In the third phase (renewal), the same settings as in the learning phase were used. For adults, the balloons were 200 × 330 px, two random colors were picked from the set of green, red, blue, and yellow, it took about 7800 ms for a balloon to reach the top, and there were six balloons on screen at any given moment. For children, parameters were adjusted to fit their ability after estimating their ability based both on prior participant data and the results of their own first block data. Thus, between two and six balloons were presented at the same time with an on-screen time between 7000 and 13,000 ms. Each block took 90 s, summing up to an experimental time of 5 min.

FIGURE 5 | Example trial from study 5 (Extinction Learning). Multiple balloons appeared on the screen and moved from the bottom of the screen to the top. In the learning and relearning conditions, all colors popped when being tapped, while in the extinction phase only a single color was poppable.

Study 6: Visuo Spatial RT

The final study we analyzed in this work was a simple visuo-spatial reaction time measurement. In this study, we intended to get a more general picture of the ability to use taps on a tablet without cognitive interference. Thus, a simple reaction time task was used where only the position and size of the stimulus varied. In each trial, a green sleeping frog appeared on the screen (see **Figure 6**, left). When tapped, the frog jumped twice before disappearing and a short sound was played. The full task consisted of four blocks of five trials each with 1000 ms ITI between trials. After three training trials, the frog first appeared centrally (condition 1), then appeared at random positions and decreased in size from 200 × 160 px (condition 2) to 100 × 80 px (condition 3) to 50 × 40 px (condition 4). If no tap was detected within 10 s, the trial was determined as "not tapped" and ended. The task took about 2 min to complete.

Analysis

The metric "tablet usage" was simply determined through a questionnaire item on the consent form participants and/or their legal guardians signed before taking part in our studies. The question "How familiar are you with devices that have a touch screen (e.g., a mobile phone or tablet)" could be answered either with "no experience," "little experience," or "much experience." To determine the "completeness" of studies, we used a mixture of observational data collected during testing and Post-test checking of each data set for missing data. First, each participant's data was checked for missing trials and a percentage of completed trials was calculated. Additionally, in each study, the experimenter noted when a child did not want to finish the study (e.g., boredom, fear of the stimuli or similar reasons). Those two factors combined yielded the relative completion rate of each participant. A special case was study 4 (Visual Search), where we expected children to only complete four of the eight experimental blocks due to the repetitiveness of the paradigm. Thus, four blocks was considered to constitute 100% completion; additional data was seen as optional icing on the cake. Because of this, as well as the fact that sometimes children wanted to repeat tasks (especially study 6), data might reflect completion greater than 100%. In such cases, we trimmed "completeness" down to 100%. In addition, for assessing completion rates, all data, including training trials, were used. How the metric "accuracy" was calculated depended on the study. In studies 1 (Sort Recall easy), 2 (Sort Recall difficult), 3 (Sort Recall Perception), and 4 (Visual Search), we were able to use the inverted error rate of each task as an accuracy measure for each participant. In study 5 (Extinction Learning), accuracy was calculated as the sum of hits and correct rejections compared to misses and (repeated) false alarms. As study 6 (Visuo Temporal RT) did not have "correct" and "incorrect" answers, we defined those trials where participants did not answer within the 10 s of presentation time as erroneous (missed trials). Training data was excluded when calculating accuracy rates, as experimenters often used training trials to explain the task to the children. Response times in studies 1, 2, and 3 were determined as the time between appearance of the stimulus and either dropping the stimulus on a categorization stack or dropping the candy on either of the images. In studies 4, 5, and 6, response time was determined between the appearance of the stimulus and either the tap on any of the nine images, on a balloon, or on the frog, respectively. To calculate response times, training trials and error trials were excluded; in the case of study 5, only hits were used. Subsequently, we compared the metrics completeness, accuracy, and reaction time to adult data to identify a potential convergence of children on adult data. This procedure allows inferring at what point it would be safe to assume an equal senso-motoric point of action when conducting tablet experiments. Furthermore, to avoid any observer-expectancy effects, the metrics and their calculation were not known to the experimenters who acquired the data, but only revealed after completion of data collection.

RESULTS

Tablet Usage

Figure 7 depicts the merged questionnaire data of all experiments. While 29% still did not have contact with tablets at the age of 2, that number steadily decreases until participants are 5 years old, where everyone had at least a little

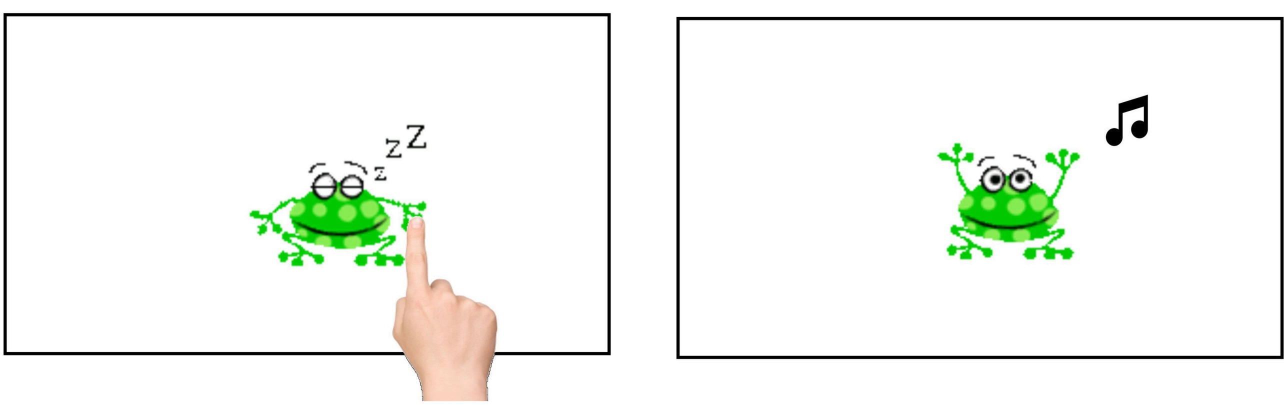

FIGURE 6 | Example trial from study 6 (Visuo Spatial RT). In each trial a sleeping frog appeared on the screen. When the frog was tapped, a sound was played and the frog jumped twice, before disappearing. Size and position of the frog varied across trials to get a more isolated measurement of tapping speed and accuracy without increasing cognitive load.

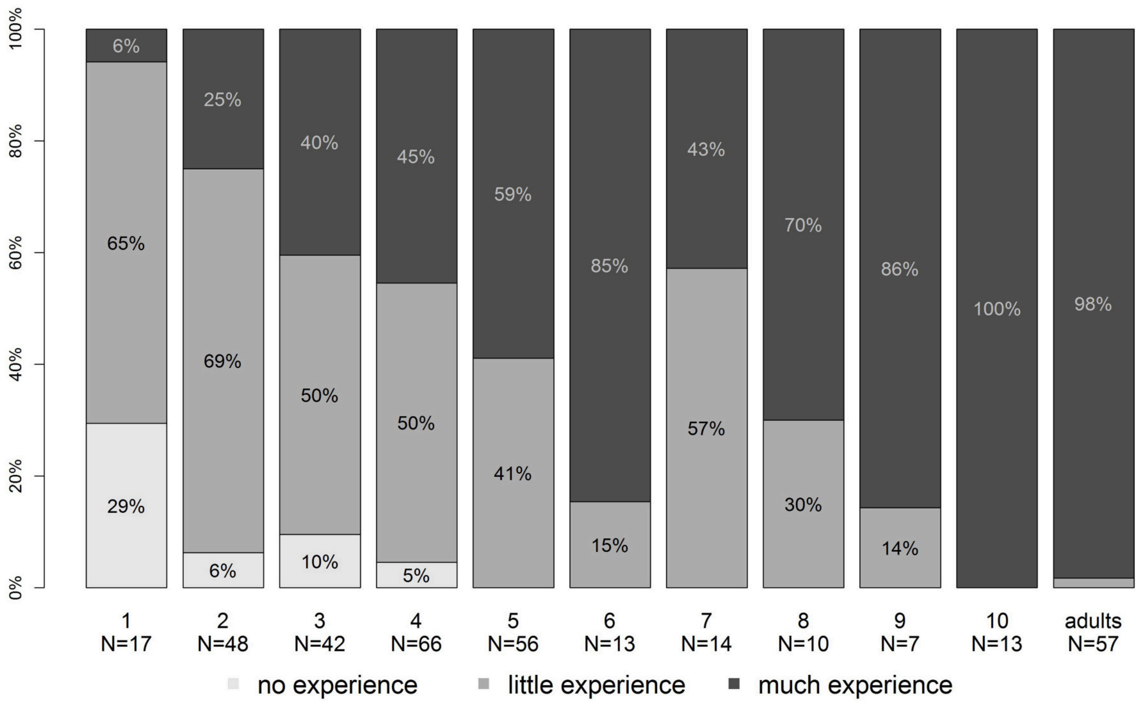

FIGURE 7 | Usage of tablets by participants. The graph depicts self-reported experience with tablet-like devices by the participants or their legal guardians, plotted against age.

experience with touch screen devices. The regular use of such devices then increases, reaching a majority around the age of 8. In short, the older the children, the more prominent is tablet use up to an age of 10, where tablet usage reaches adult levels.

Data Completeness

In general, our studies were designed to allow our (young) participants to complete them. To investigate if we reached this goal, we plotted the percentage of complete data sets for each study in **Figure 8**. Each colored line represents one study; those with multiple tasks (Sort Recall easy, Sort Recall difficult, and Sort Recall Perception) are represented with one line of identical color for each sub-task but with a varying symbol. Child data is linked to adult data with a dashed line. On average, we were able to obtain around 64% of the data we intended to acquire from 1-year-olds, about 84% from 2-year-olds and 90% for 3-year-olds. By the age of 4, almost all participants finished all of the respective trials, regardless of study length. The only notable exception was the perception task in Sort Recall Perception. Here, most children that did not complete the entire set of tasks simply ran out of time (due to data acquisition being tied to the operating hours of the schools) although some children also did not finish because they became bored due to the repetitiveness of the staircase-based task. With an average duration of 25 min (occurring after about 15 min of the two other tasks in this study) it was also the longest task of all our paradigms and was very demanding for participants. To statistically test these observations, we calculated Bonferroni-corrected t-tests that compared each age group to adult data in each task. We found significant differences in completeness between adult data and children of the ages of 3, 4, and 5 in Visual Search, 1 in Extinction Learning, and 1 in Visuo Spatial RT. Those data points that were indicated as significantly different from adult data were denoted with empty symbols in **Figure 8**, those with no difference with filled symbols. For the sake of brevity, detailed t-test results are omitted in this and the following sections, but can be found in supplemental data. Taken together, our data suggests that from the age of 2 onwards, children had sufficient tablet skills and motivation to complete the tasks they were presented with.

Accuracy

While task-specific effects in our studies are most certainly related to age, here we want to investigate the general ability of our participants to understand and correctly handle the task they were given when compared to adult subjects. This metric was defined through correct answers for studies 1–4, while study 5 (Extinction Learning) used the correctness rate based on hits and correct rejections compared to false alarms and misses. Study 6 data was defined as accurate when a tap occurred within the 10 s timeout limit. In **Figure 9** we plotted these results per age for each study. Independent of absolute, task-dependent values, the trend of our accuracy data is clearly visible: in each task, younger children exhibit a higher error rate than their older counterparts, which in turn are slightly below adult level. Especially in harder tasks (e.g., recall compared to sorting or the moving stimuli in Extinction Learning compared

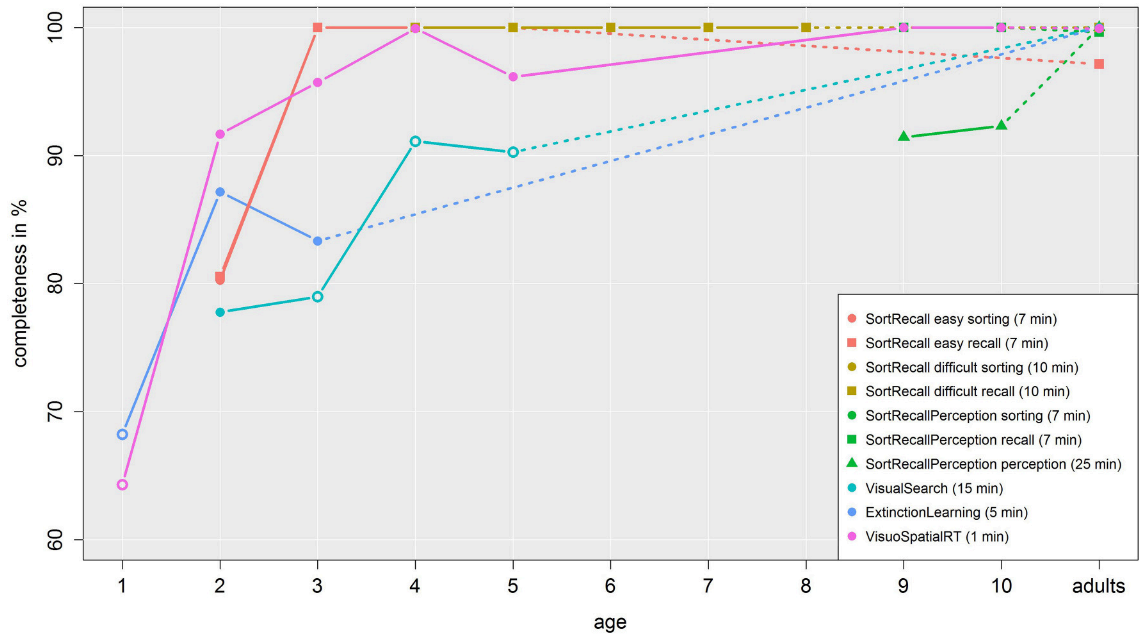

FIGURE 8 | Completeness of data. This figure shows to what extent we were able to collect data at each age. Each line represents one task in one study, while the legend includes the duration of each task. The dashed line connects children with adult data. Empty symbols denote a significant difference between children and adult data.

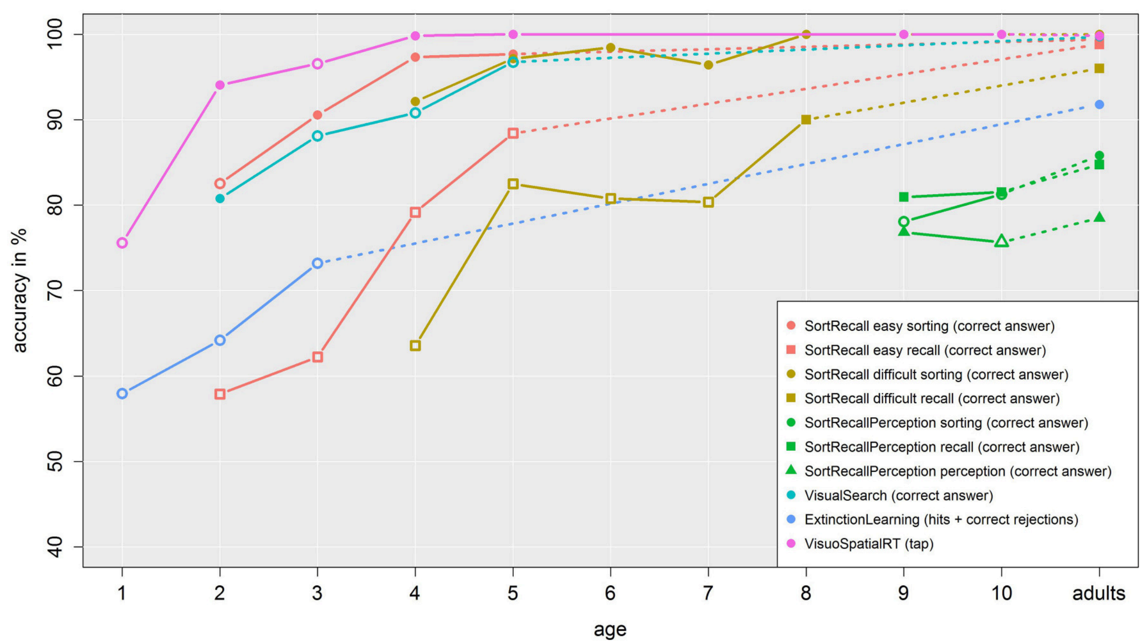

FIGURE 9 | Accuracy data. The plot shows the accuracy rate in percent over age. Each line represents a task and the same colors denote sub tasks from the same study, which are differentiated by symbol. Dashed lines connect child data with adult data. Empty symbols denote a significant difference between children and adult data.

to the static stimulus in Visuo Spatial RT), the difference is more prominent. Additionally, the accuracy rate depends on the difficulty of stimuli, as can be seen when comparing the tasks in Sort Recall easy, Sort Recall difficult and Sort Recall Perception. Those three studies used the same design and tasks, but included increasingly difficult stimuli. Importantly, none of the accuracy dependent tasks (recall, perception, Visual Search, Extinction Learning) reached ceiling or floor level for our young participants, which allows their use in investigating task-specific effects.

Statistically, Bonferroni-corrected t-tests indicated a significant difference between adults and children aged 2 for Sort Recall easy sorting, 2, 3, 4, and 5 for Sort Recall easy recall, 4, 5, 6, and 7 for Sort Recall difficult recall, 9 and 10 for Sort Recall Perception sorting, 10 for Sort Recall Perception perception, 3, 4, and 5 for Visual Search and 1, 2, and 3 for Extinction Learning, and 1, and 3 for Visuo Spatial RT. As before, we indicated these results as empty symbols; detailed results can be found in a supplemental table. Briefly, accuracy steadily increased over age but, importantly, even the youngest children performed above chance while the older children still performed below ceiling (with the exception of Visuo Spatial RT, which was designed to be as pure a measure of simple response time as possible). These results argue that all tasks were at an appropriate difficulty for their respective age ranges.

Reaction Times

Response time was defined as either the duration between appearance of the stimulus and the drag motion onto a respective target area (studies Sort Recall and Sort Recall Perception) or as the duration between the appearance of the stimulus until a tap on a target or distractor (studies Visual Search, Extinction Learning, and Visuo Spatial RT). **Figure 10** shows these results for each task plotted over age. In all tasks, response time generally decreases across development. However this change is not linear; after the age of 5, children's response times quickly converge toward adult values. Notably, there is a very clear and consistent differentiation between the three sub tasks of Sort Recall Perception across different ages, including adults. The cognitively least demanding task (perception) exhibits the fastest reaction time, followed by the sorting task, which requires slight cognitive processing, with the cognitively most demanding task, recall, exhibiting response times that are almost 2 s longer. Importantly, these response times all require the same motor action (dragging and dropping an image). Additionally, all tap tasks show a clear linear decrease in response time over age from 2000 ms (Extinction Learning, 1-year-olds), 3000 ms (Visuo Spatial RT, 1-year-olds), and 5000 ms (Visual Search, 2-year-olds) to about 1000 ms (adults).

Bonferroni-corrected *t*-tests show a significant difference in response time between adults and children at the age of 2, 3, 4, and 5 for Sort Recall easy sorting, 2, 3, 4, and 5 for Sort Recall easy recall, 4, 5, 6, and 7 for Sort Recall difficult sorting, 4, and 5 for Sort Recall difficult recall, 9, and 10 for Sort Recall Perception sorting, 2, 3, 4, and 5 for Visual Search, 1, 2, and 3 for Extinction Learning, and 1, 2, 3, 4, and 5 for Visuo Spatial RT. Details can be found in the supplement material and significant differences are indicated in the graph as empty symbols. In short, the speed of giving a correct answer increases over age. Depending on the task, 8- to 10-year-olds are already almost as fast as adults. For more details, with a specific focus on response times for tap actions, see the following section.

Visuo-Spatial Results

To further investigate the ability of children to tap on touch screens, we analyzed the results of study 6 (Visuo Spatial RT) in more detail. **Figure 11** shows the general increase in reaction time in all ages over condition, where the easiest condition was

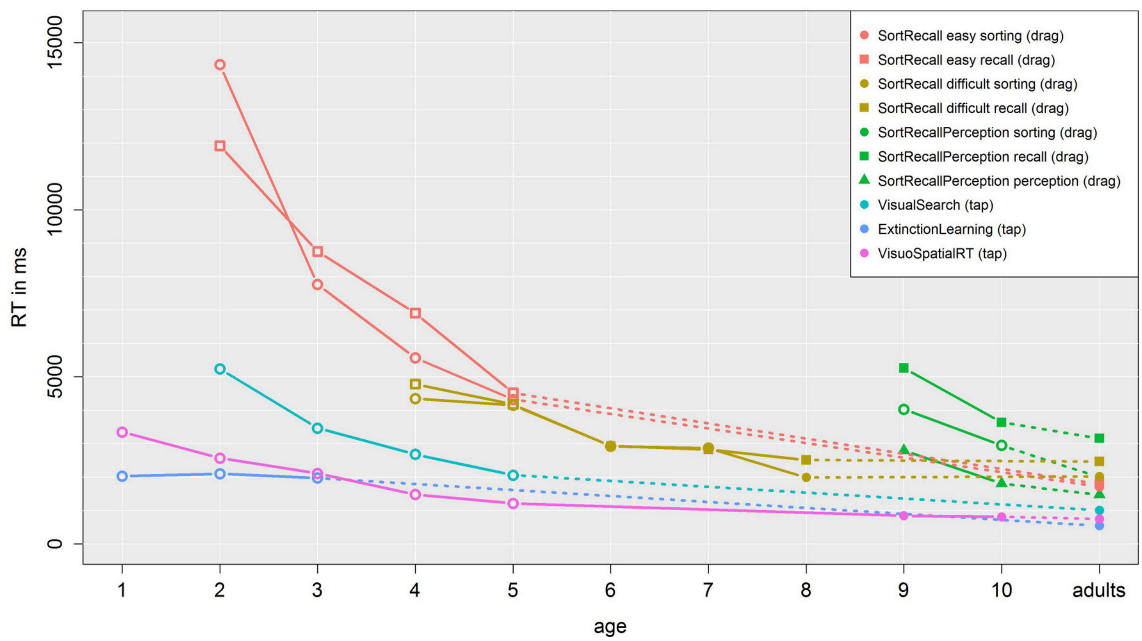

FIGURE 10 | Reaction time data. Each line represents one task, with same colors denoting sub-tasks from the same study. Dotted lines connected children and adult data, while empty symbols indicate a significant difference from the age and adult data.

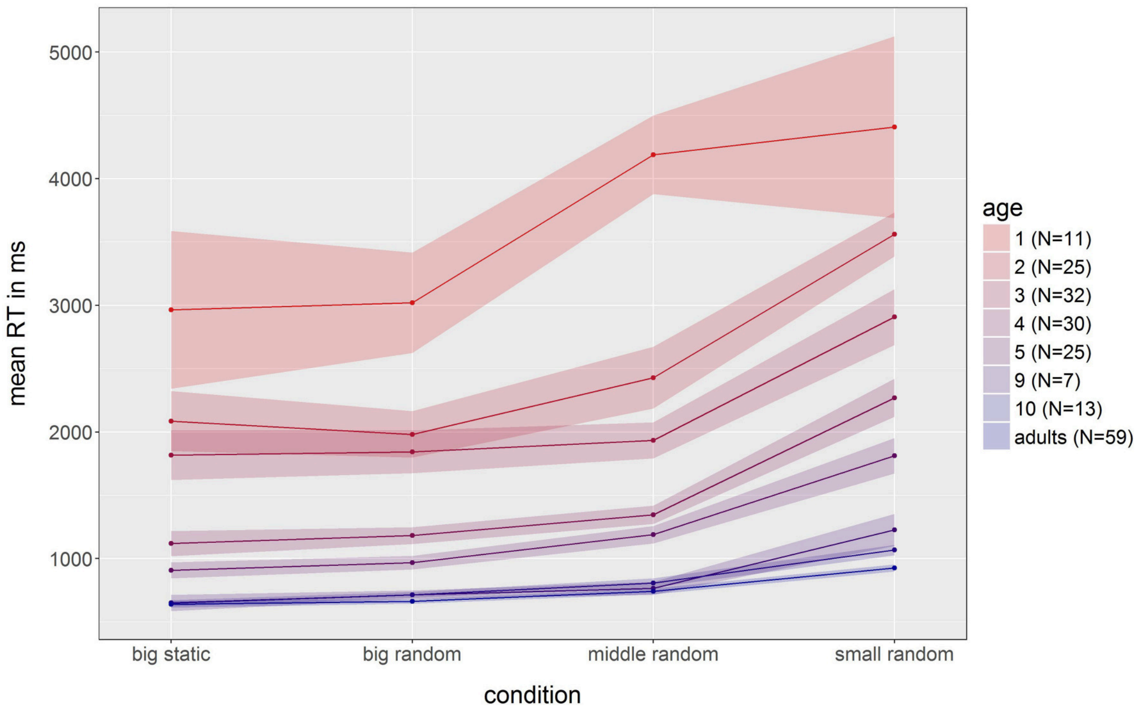

FIGURE 11 | Detailed results of study 6 (Visuo Spatial RT). Each line represents the results from one age group. Standard error is represented by the semi-transparent ribbon of the same color. The first condition started with a big, static, centrally presented stimulus that then decreased in size (big, middle, small) and appeared at a random position in the other three conditions. Colors change from red (youngest participants) to blue (adults).

a big green frog presented centrally, which then appeared in a random position in condition 2, before decreasing twice in size in conditions 3 and 4. Only data sets that had at least one answer were analyzed and data were further processed by removing training trials and misses. We find three noteworthy results: First, there is a very clear increase in speed over age. With each subsequent age group, the reaction times in all conditions become faster, up to a plateau at adult level by around 9 years of age, as reflected in significant Bonferroni corrected t-tests between 1- to 5-year-olds and adults (all $p < 0.01$), but no significant differences between 9- and 10-year-olds and adults (all $p > 0.05$). On average, 1-year-old participants exhibited reaction times that were 390% higher than those of adults, followed by a 238% increase for 2-year-olds, 186% for 3-year-olds, 99% for 4-year-olds, and 64% for 5-year-olds. Second, the data from older children, in this case 9- and 10-year-olds (13% and 9% lower speed respectively), needs to be viewed in more detail. In the first three conditions, reaction time matches adult level (between and 1% and 9% slower), but the 4th and therefore hardest condition with the smallest stimulus still shows a significant decrease in speed compared to adults (32% higher reaction times for 9-year-olds and 15% higher reaction times for 10-year-olds). Lastly, the variance in reaction times also decreases over age. When comparing data from 2-year-olds and 4-year-olds, with the same group size, there is a visible decrease in standard error.

Taken together, we argue that there is a clear, easily measurable development in the speed of motor reactions to visual stimuli presented on touch screens across at least the whole age range tested here (1- to 10-year olds) and probably beyond. Despite this, when using reasonably sized stimuli, we were able to obtain equivalent reaction times for 9- and 10-year-olds as for adults. In sum, these results support the general assumption that motor control is still developing across childhood and that reaction speed is highly dependent on age. Here, we also show that a simple RT test on a tablet device can measure these developmental changes so that cognitive researchers can take motor differences into account when assessing development in their main task of interest.

Summary

To create a one-glance summary of all metrics over all studies, we calculated a cumulative relative measure of tasks. More specifically, for the metrics tablet usage, completeness and accuracy we calculated the maximal value for each sub task and related all other results within this sub task by calculating each as a percentage of the max. To do so for the tablet usage items, we weighted them beforehand with 1 for "no experience," 2 for "little experience," and 3 for "much experience." For the response time data, we first inverted the values before applying the same method. The third degree polynomial smoothed results of this approach can be found in **Figure 12**.

As can be seen from the graph, tablet usage strongly increases between the ages of 1 and 5 to a plateau that is about 80% of adult data. Similarly, completeness shows a sharp increase between 1

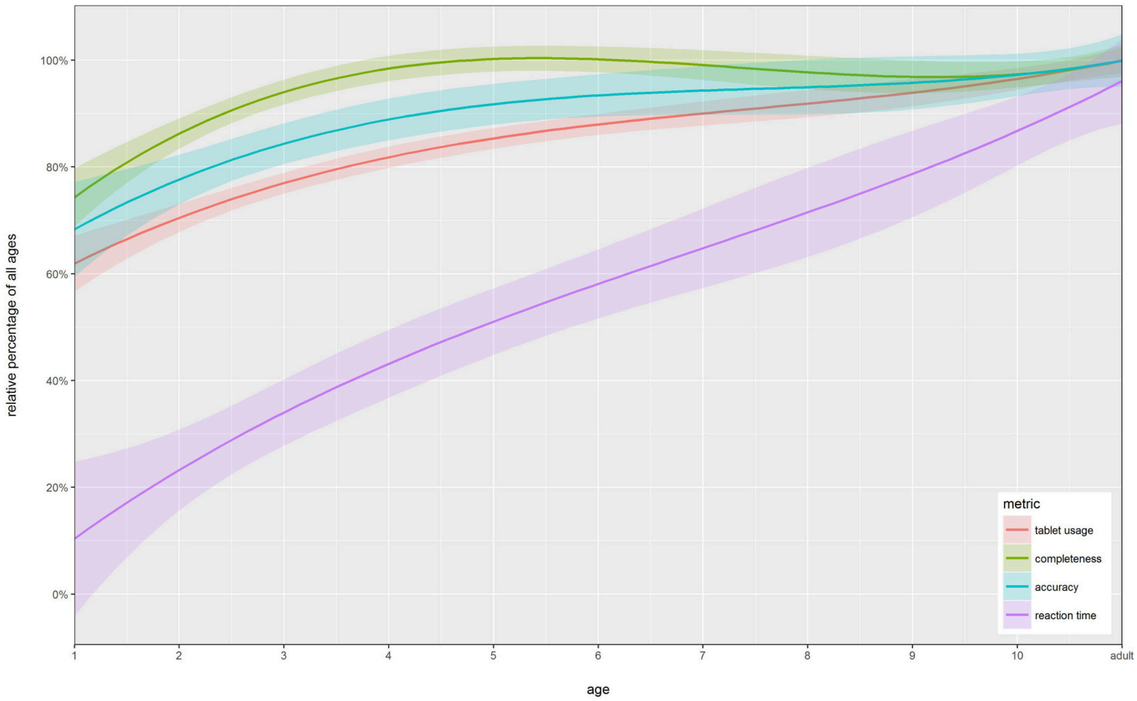

FIGURE 12 | Summary of all metrics. Cumulative metrics of all study's plotted over age. Tablet usage has been weighted to be quantifiable. Third degree polynomial smoothing has been applied, and standard error is shown as a semi-transparent area around each line.

and 4, after which on it stays at close to adult level. The local maximum of this metric around the age of 5 is due to the nature of our studies: 1 (Sort Recall easy), 2 (Sort Recall difficult), and 4 (Visual Search), all conducted with 5-year-olds, had a very high completion rate, while study 3 (Sort Recall Perception), conducted with 9- and 10-year-olds, included exhaustive sub-tasks like the perception task (see 3.2 for details) and had a slightly lower completion rate. Examining accuracy, we find it starts out at a very high level of 70% of adult level and therefore has the smallest increase over age of all our metrics, which argues that our paradigms exhibit similar difficulty across age-groups. This confirms our assumption that our tasks were appropriately difficult for each age range, while still revealing developmental change over age. The last metric, response time, shows the largest increase over age. On average, 1-year-olds exhibit about 15% of the speed at which adults are able to perform the tasks. This difference becomes linearly smaller over age, as mentioned before (see Section Visuo-spatial results for details).

DISCUSSION

In this work, we evaluated six studies that used touchscreen tablets as data acquisition devices with children between the age of 1 and 10 as well as adults. We used four metrics—tablet usage, completeness, accuracy, and reaction time—to evaluate whether tablets are an appropriate and effective method to conduct experiments and collect data in developmental psychology. In sum (**Figure 12**), we found that children have enough experience and enough motor control to use a tablet already at the age of 2 (**Figure 7**), combined with enough persistence and will to complete studies designed to be age appropriate (**Figure 8**). From the age of 5 onwards, in most tasks, participants are at ceiling for completeness, while differences in accuracy still allow us to measure developmental effects (**Figure 9**). The fourth metric, response time, can be seen to linearly improve over age until participants reach the age of 9 or 10, at which point they perform, on most tasks, at adult-like speeds (**Figures 10**, **11**). In short, while we find slight—partially task-specific—differences in the metrics we investigated, tablets seem to be a promising tool with which to acquire experimental data and begin to close the aforementioned methodological gap in developmental psychology.

As stated in Section Hardware and Software, we deployed two different types of tablets, a browser, and a combination of HTML and JavaScript to present stimuli and record input from our participants. There were two main motivations for using web technology as software in presenting our experiments. First, due to web technology's native ability to interpret and process touch events, it allowed us to implement the experiments quickly and easily, without the need to program additional interpreters or similar. Second, using web technology allows researchers to publish experiments online, making it possible for parents to participate with their children from home. Such a scenario would make the collection of large and diverse data sets much easier. However, the use of web technology comes with concerns about data security, questions about measurement reliability (Frank et al., 2016) across different platforms and screen sizes, and the need for reliable, consistent internet access during data acquisition. In the present experiment, two of these concerns were solved by using a locally installed webserver. Removing the need for internet access greatly reduced potential concerns regarding how data is transmitted and stored, as we saved the data directly on each device. Getting rid of the need to have a Wi-Fi or data connection also allowed us to conduct research in a variety of locations; a great gain in freedom, especially when compared to static, lab-based experimental computers that are the current common standard in most areas of cognitive psychology. Measurement reliability in regard to timing accuracy is a widely discussed topic in other areas of psychology. However, recent studies show that effects can reliably be reproduced using web technology, especially when using within-subject designs, as was done here (e.g., Crump et al., 2013). Finally, scientists need to be cautious with the robustness of their paradigms when designing for the tablet. Unintended gestures (e.g., dragging instead of tapping, or using two hands and simultaneously interacting with the screen) might lead to technical issues or spurious between-subject (or age) differences. In our case, this was observable in study 5, 1-year-olds surprisingly managed to crash the application in several cases due to their "taps" being rather uncoordinated hitting on the screen with both hands in parallel. Thus, precautionary measures need to be employed to allow only the actions that are intended to be measured and exclude all other possible responses, therefore making experiments "foolproof" (see Section Hardware and Software for details). Despite these cautions, in sum, we found web technology implemented on tablet devices to be a reliable and easy way to employ different kinds of paradigms.

Although general tablet usage was not our main focus, the results of our questionnaire show a clear trend toward increasing tablet usage with age: While some children between the ages 1 and 4 did not have any contact with touchscreen devices and only some used them on a regular basis, the proportion slowly but steadily became inverted from the age of 5 onwards. Our data led us to infer that nowadays, from the age of 10 onwards, almost all children as well as adults have regular, intensive interaction with touchscreen devices. This has obvious implications for conducting experiments: Children below 10 years might still be in the learning process of how to intentionally operate a touch screen, with 1-year-olds definitely having large gaps of knowledge while older children generally know how to coherently interact with the screens. More extensive research on the possible effects of unfamiliarity on acquired data should be done in order to be able to differentiate between paradigms in which expert participants might have an advantage and those where even naïve users are on equal footing. In general, our data suggests that 2-year-olds have enough experience with touch-screen devices to successfully interact with them in an experimental paradigm where simple touch responses are used. Yet, we found our three-point scale not able to differentiate tablet usage in a detailed manner. A continuous scale (e.g., hours per week) would rely less on the interpretation of participants and allow for additional correlation analysis, and therefore we suggest to employ such a scale in future investigations.

Our analyses of "completeness" support the notion that age is a good indicator of effective interaction with tablets. One-year-olds exhibit a 20–30% lower completeness rate than 2-year-olds in the same study, which quickly rises above 95% completeness by the age of 4. That the completeness of 2-year-olds in Visual Search did not yield significant results, despite being of a lower value of 3-year-olds that were significantly different to adults is attributed to the lower sample size. In general, the reasons why the youngest participants are not able or willing to participate for the full duration vary. In study 6 for example, some children were frightened of the green jumping frog we used as a stimulus. This was a surprise to us, as it was intentionally designed to be attractive for toddlers. Other children simply did not understand the task or the necessary actions (i.e., tapping the frog), despite experimenter's demonstrations during the training trials. These participants played with the tablet itself instead of paying attention to the screen and following the instructions. Combining these findings with the results of our questionnaire, we can conclude that 1-year-olds might not produce reliably robust results due to their inexperience with touch screens and inability or unwillingness to engage with the task. For older children, on the other hand, the main limiting factor was boredom. If participants were repeatedly presented with monotonous tasks, like the staircase-based perception task in our study 3, some children became uncomfortable and tired and wanted to quit the study. In addition to lack of motivation, we also experienced extrinsic limitations. Due to the duration of this task, sometimes our experimental times exceeded the time limits set by the teachers at the school or by the end of the school day. Thus, in general, we would suggest limiting experiments, whenever possible, to experimental times below 30 or even 15 min, even in older children. Still, we were pleasantly surprised that even in 1-year-olds we achieved data acquisition rates of around 65%, rising to at least 85% from the age of 2 onwards. This clearly argues that the necessary actions themselves—tapping, dragging—as well as the cognitive requirements for the tasks—sorting, recalling, perception, and visual search—are suitable for these ages. The only potential pitfall regarding completeness of data acquisition seems to be too long and/or repetitive tasks, which should be carefully considered.

Whether the tasks were also executed appropriately was investigated through our third metric, accuracy. Obviously accuracy is the task-relevant metric in nearly all studies, thus we did not expect the young participants to achieve the same level as adult subjects. Still, it would have been concerning if they produced error rates such that they were performing at chance levels. We found an increase in accuracy rates over age in all tasks of all studies. Yet, while completeness data shows two big jumps toward ceiling in very young children, in accuracy data we found a rather sequential increase over all ages. The slowly but steadily higher accuracy of participants over age argues that our paradigms were at an appropriate difficulty level and were well understood by the participants. The lack of floor and ceiling effects further suggests that developmental processes can be uncovered by further investigation of task-specific effects.

Yet, when thinking about investigating task-specific effects, one has to consider that our data is partially based on a low number of participants. The primary analysis of error rates that we presented here should not be performed in more detail, especially when considering developmental processes, with a sample size $N < 10$. Nevertheless, this finding complements our completeness data in showing that the cognitive requirements we employed in these tasks—sorting of stimuli into categories, recalling seen stimuli from memory, differentiating between stimuli based on perception, and searching for specific categories among distractors—were all suitable for the children.

With regard to reaction times, we combined two ways of analyzing the data. First, like the other three metrics, we investigated each task over age. Here, we found that on average reaction time decreased with age, as expected. Tapping speed was already close to adult level even in the very young participants, while dragging and dropping took much longer for 2- and 3-year-old children than for adults. Thus, the more complicated the expected action response is, the higher the potential difference in reaction times between ages will be. This clearly suggests that response characteristics need to be considered when designing paradigms. As a supplemental analysis, we assessed the data from study 6 in more detail and found increasing response speeds up to 9- and 10-year-olds, who were only slower than adults in a condition with a very small stimulus. Logistically, we would recommend providing targets that are big enough for children to tap and drag easily to avoid frustration and contaminating cognitive data with motor effects. Nevertheless, these findings point to the importance of identifying a threshold at which adults and children operate on a common ground in senso-motoric ability. When considering taking reaction times as an experimental metric, one has to assure that differences do consist of cognitive differences on the one, but importantly motoric disadvantages on the other hand. Unfortunately, this important differentiation—can the decrease in response times with age across tasks can solely be attributed to motor abilities or a general increase in cognitive and attentional capabilities—cannot fully be covered by our data. To investigate this issue, we would need to supplement our general reaction time task with another task that sequentially increases cognitive load—over all ages. In this case, we could single out whether an increase of reaction time is static, or becomes larger through increased mental resource requirements.

Lastly, we wanted to take another look at the advantages of using tablets in developmental psychology. In all our studies, we found the children (except some percentage of 1-year-olds) to be very engaged and naturally interested in interacting with the touch screens. This confirms results of previous studies (e.g., Frank et al., 2016), but also suggests that tablets may provide a way for closing the methodological gap presented before: Essentially we can, through tablet-mediated experimentation, conduct psychophysical studies from the age of 2 onwards with only a few limitations with regards to length and stimulus material. Children are fascinated by the "gamified" experiments, easily become engaged and decide by themselves—sometimes very clearly—when they have had enough. Combining these characteristics with the portability of touch screen tablets and the ease of data acquisition across many places with many children—e.g., day care, kindergarten, schools or museums—yields high amounts of data with relatively little effort in a pleasurable way for both experimenters and participants. Additionally, this kind of flexible testing in comfortable environments may be especially helpful when thinking about acquiring data from special populations —for instance children with autism or other social impairments for whom role-plays or eye tracking paradigms may be unsuitable. All these advantages do not only apply for classical research studies, but also open up the field of online data acquisition for young children by publishing tablet-based online experiments that can be "played" from home; without the need for lengthy instructions or the presence of an experimenter.

Summing up, through an array of 6 experiments we found that tablet-based experimentation might prove to be an invaluable tool for conducting research with children. Keeping tasks interactive, below 15 min in length, and based on metrics like error rates should produce reliable and robust data from the age of 2 onwards. Mobility, low cost and easy implementation put touch screen paradigms on par with already established methods like role-plays and eye tracking. Further work should investigate potential effects of tablet familiarity on results, the acceptable limits of children's endurance, potential interactions between the development of cognitive load and motor development in reaction time measures, and the publishing and distribution of such experiments through the internet to the wider public. Despite the long road ahead, we already can recommend integrating new technologies in developmental research and the use of tablet-based experimentation to obtain data we might not be able to acquire otherwise.

AUTHOR CONTRIBUTIONS

KSe: Programming, design, analysis of all studies. MN: Design of all studies. KSo: Design, material, data acquisition of study 1. RR: Design, material, data acquisition of study 2. LM: Design, data acquisition of study 3 and data acquisition of study 6. HP: Design, material, data acquisition of study 4 and data acquisition of study 6. ST: Design, material, data acquisition of study 5 and data acquisition of study 6. TM: Design of study 4. KK: Design, material of studies 1 and 3, piloting of study 3. SW: Design, analysis of all studies. All authors participated in writing and approved the final version of the paper.

FUNDING

This work was supported by a PhD scholarship of the German Academic Scholarship Foundation (Studienstiftung des deutschen Volkes) to KS and grants from the German Research Foundation (Deutsche Forschungsgemeinschaft, WE 5802/1-1) and the Mercator Research Center Ruhr (AN-2014-0056) to SW.

SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: http://journal.frontiersin.org/article/10.3389/fpsyg.2016.01021

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Conflict of Interest Statement: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

frontiers in Psychology

OPINION
published: 06 June 2016
doi: 10.3389/fpsyg.2016.00839

Should Touch Screen Tablets Be Used to Improve Educational Outcomes in Primary School Children in Developing Countries?

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Keywords: mathematics, hand-held tablets, ICT, developing countries, intervention, early years, literacy

The 2030 Agenda for Sustainable Development aims to "ensure inclusive and equitable quality education and promote lifelong learning opportunities for all" (United Nations, 2015). Whereas, the principal focus of global education planning since 2000 had been on getting children into schools, sustainable development goal 4 (above) reflects concerns about quality. As improving learning outcomes starts to receive heightened policy focus, it becomes imperative to consider the types of intervention that can be most effective in raising learning outcomes, particularly in settings characterized by poor resourcing and persistent low attainment levels. Here, we consider if touch screen tablets can be used to improve educational outcomes in primary school children in developing countries. We focus on early maths attainment in Malawi as one of the most dramatic examples of the current learning challenge.

OPEN ACCESS

Edited by:
Joanne Tarasuik, Swinburne University of Technology, Australia

Reviewed by:
Karen J. McLean, Australian Catholic University, Australia

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Specialty section:
This article was submitted to Developmental Psychology, a section of the journal Frontiers in Psychology

Received: *15 April 2016*
Accepted: *19 May 2016*
Published: *06 June 2016*

Citation:
Hubber PJ, Outhwaite LA, Chigeda A, McGrath S, Hodgen J and Pitchford NJ (2016) Should Touch Screen Tablets Be Used to Improve Educational Outcomes in Primary School Children in Developing Countries? Front. Psychol. 7:839. doi: 10.3389/fpsyg.2016.00839

CONTEXTUAL BACKGROUND

Malawi is in desperate need of educational reform (UNESCO, 2015). Its first democratic elections in 1994 saw education become a core electoral issue, with parties seeking to outbid each other on their educational promises. This resulted in a free primary schooling policy, introduced at very short notice, which got millions of children into school, but ultimately could neither deliver good education nor keep learners in schools. More than 20 years on, primary education in Malawi still suffers from high repetition and drop-out rates, poor supply or lack of essential teaching and learning materials in most schools, and severe shortages of qualified teachers. These factors contribute to poor internal efficiency of the education system, as well as impacting negatively on early grade numeracy acquisition in Malawian pupils, a key foundation skill for later learning. Girls and children with special educational needs are particularly vulnerable in this education system, which results in vast inequalities across pupils.

In 2007, The World Inequality Database on Education reported that only 40% of all primary school children in Malawi attained the minimum learning standards. Despite some improvements in recent years, the low level of primary mathematics attainment in Malawi is a significant and continuing concern. In the 2007 Southern and Eastern Africa Consortium for Monitoring Educational Quality (SACMEQ) survey at Grade 6, Malawi's mean mathematics score of 447 was well below the average of 510 for countries participating in the survey (Milner et al., 2011a). Less than 50% of students reached at least the SACMEQ basic numeracy competency level by the end of primary school. Key factors appear to be the availability of resources, particularly textbooks, and the quality of teaching (Chimombo, 2005; Milner et al., 2011b). This suggests that an early intervention, focused on basic arithmetical skills and concepts, that does not rely too heavily on teacher quality might be an effective way of addressing the challenges faced in primary mathematics in Malawi.

COULD DIGITAL EDUCATION TECHNOLOGY (DET) PROVIDE AN INNOVATIVE SOLUTION?

DET has been used with the aim of raising educational attainment in interventions across high income and developing countries. Despite a great deal of government money being spent on DET (Law et al., 2008), outcomes on learning are mixed even for relatively small-scale and well-designed interventions. A review of 74 DET projects attempting to raise mathematics performance across a variety of countries found modest effect sizes for improvement (Cheung and Slavin, 2013). This may be because the technology has not generally had a strong focus on pupil learning. Several small-scale studies have found positive effects for computer use in schools for mathematics (Banerjee et al., 2007; Räsänen et al., 2009; Praet and Desoete, 2014; Sella et al., 2016) and in other domains, including literacy (Ho and Thukral, 2009; Kaleebu et al., 2013). Probably the most well-known and widespread use of DET in the classroom is the One Laptop Per Child (OLPC) intervention. However, this project has had limited success due to poor implementation and lack of teacher training. In Alabama, US, the programme failed due to lack of Internet access in schools and poor support for repairs (Warschauer and Ames, 2010). In Peru OLPC succeeded in increasing the numbers of computers available to students, but no effects were found for improving mathematics or language skills (Cristia et al., 2012). In Rwanda (Fajebe et al., 2013) and Tanzania (Apiola et al., 2011), problems included a lack of both teacher training and child-directed implementation. Teachers often saw themselves, rather than the pupils, as the primary laptop users. In contrast, recent interventions focused on touch screen tablet technology used directly by pupils have shown promising results.

A review of 23 studies published since 2009, which used touch screen tablet technology for improving academic performance in children aged 5–18 across high income and developing countries, found large positive effect sizes in favor of the technology compared to normal classroom practice for a range of subjects (Haßler et al., 2015). Use of tablet technology also improved mathematics performance in pre-school children in a teacher-led intervention in the US and children became more independent learners (Schacter and Jo, 2016). Berkowitz et al. (2015) also found home use of tablets improved mathematics skills in 5–6 year-old children. Other benefits of touch screen tablets include easier use for young children in respect of motor skills (Cooper, 2005; Donker and Reitsma, 2007; Kucirkova, 2014; Outhwaite et al., under review).

UNLOCKING TALENT THROUGH TECHNOLOGY

To take advantage of the potential benefits of using touch screen tablets to address the issues of low educational attainment and resources and variable teacher quality in Malawi, the Ministry of Education, Science and Technology in Malawi is implementing a new and innovative mobile technology—"oneclass"—across 68 primary schools in partnership with an international charity, Voluntary Service Overseas (VSO), and onebillion, the UK charity behind the technology. All pupils from standards 1 and 2 in the participating schools will use the interactive apps developed by onebillion as part of their mathematics education.

ONECLASS TECHNOLOGY AND INTERACTIVE MATHS APPS

This technology consists of a learning center and a series of interactive, child-centered, maths apps that has been developed by the non-profit education publishers, onebillion, for 3–6 year olds. The maths apps are delivered to individual children through an Apple iPad mini connected to a set of headphones. Designed especially to be easy for schools to implement, the software provides clear instruction through a virtual teacher speaking in the local language, at an age-appropriate level, and guides pupils progressively through a series of activities based on the national curriculum. The learning center is a specially designed classroom equipped with solar power to enable children to use the maths apps throughout the day, even in remote rural regions that are off-grid. Remote monitoring ensures that children are using the maths apps and records their progress as they work through the apps. This information is fed back to their teachers, which enables teachers to direct attention to children that become halted on a particular part of the maths apps, and children who are making slow progress. A solar-powered projector in the learning center allows teachers to work with groups of children on a particular topic and provide additional support to slow learners. Even teachers with little subject knowledge can deliver the maths apps to small groups of pupils, thus optimizing efficiency of teaching time whilst delivering high-quality mathematics education to all children.

EVIDENCE-BASE FOR EFFECTIVENESS

The maths apps developed by onebillion for oneclass have been trialed in Malawi at the pupil level within one urban primary school (Pitchford, 2015). A Randomized Control Trial (RCT) was conducted with 283 primary school pupils spanning standards 1–3. The intervention ran for 8 weeks. Compared to control children receiving normal practice, significantly higher attainment was shown at post-test by children with the maths apps, on both conceptual knowledge (4% higher attainment, Cohen's $d = 0.23$) and curriculum knowledge (18% higher attainment, Cohen's $d = 0.75$). Girls responded just as well to the mathematics intervention as did boys, demonstrating that this technology could prevent the gender disparity that is currently evident in Malawi education.

Despite a radically different educational and cultural context, many children in the UK also struggle to learn basic mathematical skills. A "tail of underachievement" exists amongst disproportionate groups of underachieving pupils (Tymms and Merrell, 2007, p.13), particularly children from low-income areas (Anders et al., 2012). Yet, comparable results with the onebillion maths apps to those found in Malawi were shown in a small pilot study conducted in a primary school in England.

A group of 61 pupils aged 4–5 years used the maths apps for 6 weeks as a supplementary early intervention approach to address mathematics underachievement (Outhwaite et al., under review). Significant learning gains in both conceptual knowledge (5% increase, Cohen's $d = 0.31$) and curriculum knowledge (22% increase, Cohen's $d = 1.01$) were found immediately post-intervention, and further learning gains were shown at 4 months later, at delayed post-test (conceptual knowledge increased a further 5% Cohen's $d = 0.76$ and curriculum knowledge increased a further 6% Cohen's $d = 1.07$). Learning gains were not influenced by the child's income background.

These two studies demonstrate proof of concept of a measureable impact of the oneclass intervention on mathematical attainment in primary school pupils in both Malawi and England. This cross-cultural evidence illustrates generalization of the effectiveness of this intervention across extremely different contexts and highlights the potential for this intervention to have global reach.

MOVING TO SCALE

The programme in Malawi has now moved to a medium scale trial that also sees the introduction of a new series of apps designed by onebillion to support literacy acquisition. To effectively assess scalability, we argue that new research is needed to show measurable impact on standardized assessments of numeracy and literacy and across the curriculum more broadly. Consideration of how primary school teachers cope with pupils with numeracy and literacy skills greater than they are used to is also required, as is the impact this has on pedagogical practice and curriculum development. In addition, consideration of how this technology might be used to raise learning outcomes in pupils in challenging contexts is needed, to ensure the intervention is tailored for all children, regardless of location and wealth. Finally, a cost-benefit analysis is required, to determine if the potential advantages of raising mathematical and literacy standards in primary school children in the long-term outweigh the costs of implementing this technology in a low resourced country.

CONCLUDING THOUGHTS

It is estimated that 250 million children worldwide do not possess the basic numeracy and literacy skills required to live a healthy and productive life and contribute toward economic growth (UNESCO, 2014). We have identified the possibilities that digital education technologies might have in increasing early learning outcomes in developing countries such as Malawi. We argue that to better understand the efficacy of using touch screen tablet technology to raise pupil learning outcomes research is needed that focuses not only on pupil learning outcomes, but also on critical aspects of implementation, such as teachers' use of and attitudes toward tablet technology and the embedding of tablet technology within the country's education system. These studies are essential in expanding our understanding of how touch screen tablet technology may help to reduce the challenges of underachievement in low resourced contexts. Studying in detail a country like Malawi, with all the challenges in its education system, presents an opportunity to illuminate the salient features of a successful digital integration within an education system in a low resourced country. Comparing the implementation of this technology across countries that have considerably different education systems, such as Malawi and the UK, enables generic features of implementation to be differentiated from country-specific factors. These generic and specific factors should then be used to test and successfully implement a theory of change.

Solar-powered touch screen tablet technology could prove to be a successful method for raising educational attainment in developing countries, offering sustainability and equality as countries strive to meet the 2030 objectives. However, the crucial factors of training teachers to use the technology effectively, management and resourcing of such large-scale projects, and the embedding of technology within education systems all need to be successfully addressed.

AUTHOR CONTRIBUTIONS

All individuals listed as authors of this opinion piece have: Contributed substantially to the conception and design of the work; Drafted the work or revised it critically for important intellectual content; Have given final approval of the version to be published; and Agree to be accountable for all aspects of the work in ensuring that questions related to the accuracy or integrity of any part of the work are appropriately investigated and resolved.

FUNDING

This work was supported by funding from Voluntary Service Overseas (Grant: MWI-14/0019 Unlocking Talent through Technology: Improving Learning Outcomes of Primary School Children in Malawi).

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Conflict of Interest Statement: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

frontiers in Psychology

ORIGINAL RESEARCH
published: 10 May 2016
doi: 10.3389/fpsyg.2016.00690

Parent Scaffolding of Young Children When Engaged with Mobile Technology

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Shared parent–child experiences while engaged with an iPad^{TM} were examined to determine if and then how parents interact with their children when using mobile digital devices. In total, 104 parent–child dyads participated in an observation session where parent–child interactions using the touchscreen tablet device were video recorded in order to observe first-hand the supports and exchanges between parent and child (age range 46.21–75.9 months). Results indicate that parents provide a great deal of support to their children while interacting with the touchscreen tablet device including verbal, emotional-verbal, physical and emotional-physical supports. The types of support offered did not differ as a function of parent gender or experience with mobile devices (users versus non-users). Overall, parents rated their own experience engaging with the touchscreen tablet and that of their child's positively. Additional survey measures assessed parents' perceptions of their child's technology use and attitudes regarding optimal ages and conditions for introducing and using technology. Most parents indicated a preference for very early introduction to mobile technologies. Implications of these findings are discussed.

Keywords: parent–child interactions, shared-media-engagement, children and technology, use of mobile devices, iPad

OPEN ACCESS

Edited by:
Joanne Tarasuik, Swinburne University of Technology, Australia

Reviewed by:
Rebekah Richert, University of California, Riverside, USA
Ruth Ford, Anglia Ruskin University, UK

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Specialty section:
This article was submitted to Developmental Psychology, a section of the journal Frontiers in Psychology

Received: *28 January 2016*
Accepted: *25 April 2016*
Published: *10 May 2016*

Citation:
Wood E, Petkovski M, De Pasquale D, Gottardo A, Evans MA and Savage RS (2016) Parent Scaffolding of Young Children When Engaged with Mobile Technology. Front. Psychol. 7:690. doi: 10.3389/fpsyg.2016.00690

INTRODUCTION

In our increasingly technologically advanced world, children are gaining exposure to computer-based technologies earlier and with greater frequency than in previous generations. For example, Carson et al. (2013) found that children 2–4 years of age spend an average of 8.4 min per day engaged with computers. Kabali et al. (2015) found that 60% of parents let their children play with mobile media while running errands, 73% while doing chores around the house, and 65% used mobile media to calm their children. Early interaction with computers is a global phenomenon with the proportions of 3–4-year-olds going online ranging from 25% in the United States to 78% in the Netherlands (Holloway et al., 2013). Concomitant with the ubiquitous presence of computers, is the development of increasingly smaller and yet more sophisticated mobile technologies such as touchscreen tablets and smartphones. These devices permit children access to portable, flexible, and intuitive digital media (e.g., Rideout, 2013). In concert with advances in the development of devices is a proliferation of software programs designed to promote exploration, discovery, play, and development of skills specific to cognitive and social development. It is not surprising then that many parents are turning to computer technology as a means of helping their children to learn and/or entertaining them. Yet, unlike other shared engagement contexts such as shared book reading, or co-viewing television, we know very little about how parents interact with their young children with mobile devices. Given the presence and early introduction of mobile technologies such as touchscreen tablets in the everyday lives of children, it is important to examine and understand how children's earliest interactions with these mobile computer technologies unfold. The present study investigated parental scaffolding when interacting with their children and mobile devices, specifically iPads^{TM}, in an informal setting.

The use of mobile devices may be best facilitated if scaffolding from parents is present. Scaffolding refers to the use of techniques or tools that would allow a child to reach a particular goal that would otherwise be unattainable through unassisted efforts (Wood et al., 1976). Vygotsky (1978) envisioned that guided interactions (e.g., instructional dialog) with an adult could afford a higher level of thinking within the child's zone of proximal development. In other words, presenting children with tasks that are slightly above their current competence (tasks that are challenging but not overwhelming) while assisting them as needed permits them to achieve and learn beyond what they could do if unaided by an adult (Kohlberg and Mayer, 1972; Hogan and Pressley, 1997; Neumann et al., 2009). Yelland and Masters (2007) identified three different types of scaffolding that occur during interactions with stationary computers: *cognitive, affective, and technical scaffolding*. Cognitive scaffolding involves modeling and asking questions by the parent and facilitates children's understanding of concepts. Affective scaffolding involves provision of encouragement and feedback. Technical scaffolding refers to effective learning strategies that are built into software design such as immediate feedback and automatic leveling (Grant et al., 2012). The present study expands this understanding of parental scaffolding by examining scaffolding observed in a mobile technology learning context.

Extant research supports the learning potential provided through scaffolding in computer-based learning contexts. For example, the physical introduction to stationary desktop computers was observed to be easier when young children were initiated to the technology while being seated on a parent's lap with the parent operating the devices (i.e., mouse, keyboard), and later transitioning to the children's independent use of the computer devices (Calvert et al., 2005). When children acquired the skills needed to control their own activities, they showed greater attentiveness to the tasks and activities than when adults were in control (Calvert et al., 2005). Similarly, in a recent study, pre-test to post-test gains were observed for children's device specific skills when parents supported their children's device skills while using stationary desktop computers (Flynn and Richert, 2015). These children also demonstrated cognitive gains for software related content when their parents provided support to enhance understanding of the software content. Thus, parental scaffolding, that encourages children to become independent in controlling their own actions when using computers and provides support in the cognitive tasks at hand, promotes learning.

Interestingly, Flynn and Richert (2015) identified the multiple tasks associated with stationary desktop computers as having the potential to overload children's working memory and as such interfere with their ability to learn content. The intuitive nature of mobile touch screen tablet devices such as iPads^{TM} reduces the mental and spatial demands required to operate and navigate the device. For example, the touch and swipe actions required for touchscreen tablets remove the complex spatial knowledge required to associate actions with the mouse or keyboard to actions on the screen. These reduced cognitive demands should increase attention to content, and potentially promote greater and more immediate learning with mobile tablet devices than with desktop computers. In addition, the reduced technical demands needed to operate and navigate tablets might also influence the types of scaffolding offered by parents, as attention shifts from 'learning how to use the technology' to 'using the technology to learn.'

Once children acquire the skills to use technology independently it is important that adults monitor and support the ongoing use of the device and software programs to maximize children's engagement, learning and safety (Espinosa et al., 2006). Promoting these kinds of self-regulatory behaviors in computer-based learning contexts is consistent with expectations in more traditional non-media based learning contexts. Indeed, the ability to be a self-regulated learner is one of the most important factors that separates children who are "successful learners" from children who are "less successful learners" (e.g., Paris and Paris, 2001; Zimmerman, 2002). Research that informs our knowledge about successful learning has been generated primarily from traditional non-media based learning contexts with school-aged children. However, interactions in the home also provide important opportunities for learning both when parents actively and intentionally provide instructional opportunities for their children and, perhaps more frequently, through incidental learning opportunities. Both intentional and incidental learning opportunities allow children to gain exposure to and experience with the precursor skills for self-regulation. Given the increased presence of mobile technologies which permit learning in multiple contexts, sometimes referred to "here and now" learning (Martin and Ertzberger, 2013), it is therefore important, to determine how parents support and encourage foundational skills associated with self-regulated learning in a mobile technology learning context.

Vygotsky (1978) viewed tools of the culture as key mechanisms through which we facilitate the acquisition of higher mental functions. In this regard, the presence of computer-based technological devices and, in particular, recent technologies such as touchscreen tablets, smartphones, and other mobile devices may be viewed as tools of the culture in today's Western societies. These devices are used to communicate, educate, entertain, and facilitate social interactions and work. As such they serve multiple purposes, some of which directly support and advance higher mental functions. Understanding when parents introduce these cultural tools to their young children and identifying parental supports that facilitate early interactions with these technologies may be key to understanding how these tools are best used to facilitate learning.

Parents own familiarity and skills with technologies also are an important consideration when trying to understand how cultural tools are shared across generations. It could be expected that more knowledgeable and skilled parents might engage their children differently than parents with less knowledge or skills and these differing interactions could alter the learning experience provided to their children. In the present study, parental familiarity with these cultural tools was examined to further understand the impact of familiarity on the exchanges that occur when parents and children are mutually engaged with mobile technology.

Mobile touchscreen tablets are designed in such a way that even very young users can use them easily. Touch-sensitive devices allow for an easier to use and more intuitive interface for children (McManis and Gunnewig, 2012). The size and mobility of the device permits children the flexibility of laying the tablet in their lap, on the floor, or moving with it to any area within their home (their bedroom, their play area, etc.). In addition, the interactive multimedia capabilities of touchscreen tablets can stimulate visual, auditory, tactile, and kinesthetic sensory systems. As well, the response to children's input is instant, providing immediate feedback (Cooper, 2005; Tahnk, 2011). In effect, these features enable children to quickly learn to use the technology and explore new things, learn new skills, and gain knowledge (McManis and Gunnewig, 2012). Affordances inherent in intuitive devices such as touchscreen tablets provide a context where early introduction is not only likely but expected. Low costs, portability, increasing availability of internet connectedness and a host of available applications make it probable that many parents will be using these mobile devices and that traditional gaps based on socio-economic status may no longer be apparent (e.g., Kabali et al., 2015). However, little research has examined the use of mobile devices with young children especially in the home or by parents (Plowman et al., 2012). Some research studies have examined parent–child interactions with mobile devices such as a LeapPad^{TM} (e.g., Eagle, 2012) and e-books (e.g., Korat and Or, 2010). Where the literature becomes sparse, however, is in examining the interactions between parent and child while using a touchscreen tablet computer. In particular, parents' scaffolding and support strategies and behaviors, as well as the impact of their familiarity with the mobile device (e.g., novice users as opposed to experienced users) have not been examined.

A great deal of research shows that parents desire to support their children's learning and seek to provide positive learning environments for their children (Evans and Shaw, 2008; Neumann et al., 2009; Davies, 2011; Eagle, 2012). Parents also view the home and their role as being highly influential in children's development. For example, over a third of parents rated themselves as being primarily responsible for children's literacy development (Evans et al., 2004). Evidence in other domains supports the important role parents play in their children's learning. For example, when parents use more spatially descriptive words (e.g., long, small) during joint activities, their children demonstrate long term gains in spatial word production and competence (Pruden et al., 2011). Learning in the home can be intentional or incidental. The spontaneous and incidental learning that takes place with young children in their home environments is likely to be facilitated by mobile devices as opposed to stationary desktop technology, which requires more skills, space, and planning to use jointly. To fully understand the impact of touchscreen tablets in the context of the family, the present study explored parent–child shared interaction to uncover how parents engage and support their children with these devices.

The Present Study

Shared parent–child experiences while engaged with an iPad^{TM} were examined to determine if and then how parents interact with their children when using mobile digital devices. Survey measures assessed parents' perceptions of their child's technology use and parent's attitudes regarding optimal ages and conditions for introducing and using technology. A 10-min observational session of mothers and fathers allowed for a first-hand examination of parental scaffolding when using mobile tablet technology with their young children. Given the exploratory nature of the present study, the key research questions involved examining and documenting the different types of supports that parents provided children when engaged interactively using an iPad^{TM}. Further, we explored whether parents experienced in the use of mobile devices (users) differed from inexperienced parents (non-users) in the types of supports they offered their child. We also assessed, whether gender differences existed between mothers and fathers and the types of interactions/scaffolds they provided their children. Finally, we examined whether scaffolding behaviors varied according to individual characteristics of the child or parental perceptions of technology.

MATERIALS AND METHODS

Participants

In total, 104 parent–child dyads, 72 mothers ($M_{age} = 35.40$ years, $SD = 4.81$) and 32 fathers ($M_{age} = 37.10$ years, $SD = 4.85$) participated in one interactive touchscreen tablet play session with their 2–6 years old child. There were no significant age differences between mothers and fathers, $t(102) = 1.86$, $p = 0.07$. Most parents indicated some level of higher education: college diploma (13.5%); undergraduate degree (35.6%); Master's degree (24%); doctorate degree (6.7%); or a post-doctorate (8.7%). A smaller proportion of the sample reported some post-secondary education (6.7%) or a high-school diploma (2.9%). Two participants did not report their education level. Among the parents, 76% self-identified as being familiar with the touchscreen tablet device they were asked to use in the observation session ($n = 28$ males, $n = 51$ females) and 24% were new to the mobile device ($n = 4$ males, $n = 21$ females). Those who self-reported familiarity with touchscreen tablet devices were coded as "users" and those unfamiliar with the devices were considered "non-users" in subsequent analyses. In addition, 20% of non-users ($n = 5$) did not own any computer, laptop, mobile tablet, or iPad^{TM}.

Children included 50 girls ($M_{age} = 46.21$ months, $SD = 13.22$, range = 24.3–68.9 months), and 54 boys ($M_{age} = 44.59$ months, $SD = 14.92$, range = 22.8–75.9 months). Overall, there were 32 children under 35 months of age, 31 children aged 36–48 months, 18 children aged 49–60 months, and 20 children over 60 months of age. There was no significant age difference between girls and boys who participated in the study, $t(102) = -0.58$, $p = 0.56$. Participants were recruited from early childhood education and daycare centres in a mid-sized Canadian city. All participants spoke English and used English throughout the observation session. This study was reviewed and approved by a University ethics review board. All participants were treated in accordance with APA ethical standards and were informed of their voluntary participation in all aspects of the study including their choice regarding whether or not to answer any questions on the survey or to participate in the play session.

Materials

Materials included two surveys (pre- and post-observation) and the observation session.

Pre-Observational Survey

The pre-observational survey assessed: demographic information (parent's gender and age, the child's gender and age, and the parent's highest level of education), and parental beliefs regarding the introduction of technology for their child. Timing for the introduction of technology for their children was assessed by asking parents to identify at what age they would introduce technology to their child with answer options that increased in 6-month increments from "Birth" to "After 6 years of age."

Technology

Each parent–child dyad used one iPad^{TM} (Model A1430, version 5.1.1 9B206 operating on iOS 6.1.2). In addition to default applications/software typically available on an iPad^{TM}, 12 children's reading- and math-based applications were downloaded. The 12 applications were chosen based on positive user reviews and ratings. The iPad^{TM} was housed in a spongy jacket called "iGuy^{TM}" shaped like a figure with sponge arms and legs. Apart from protection, the jacket enhanced maneuverability by allowing the iPad^{TM} to be held by arms. The case/jacket and also allowed the device to stand independently on its feet when placed on a flat surface.

Video recordings of observation sessions were made using three cameras. Two small cameras were located at either end of the room providing a full, length-wise view of the entire room, and a third small camera provided a view from an elevated position.

Post-Observation Survey

The post-observation survey was comprised of 10 questions. Two forced-choice (yes/no) questions assessed whether parents allowed their child to use mobile technologies and if they downloaded programs for their child. For parents who responded "yes" to downloading applications, there was a further prompt for parents to select from 15 possible choices all of the reasons they use for supporting their decision to download applications for their child (see **Table 2** for a list of these rationales).

As a fidelity measure, parents were asked to rate how closely the observation setting reflected typical interactions with their children when engaged with technology using a 5-point Likert-type scale with anchors ranging from "Not at all similar" to "Almost the same."

Four questions assessed familiarity with, interest in and ease of use of the iPad^{TM}. Specifically, parents were asked to identify whether they owned a desktop computer, a tablet (i.e., iPad^{TM}, PlayBook^{TM}, etc.), both or none of these devices. Parents were also asked, "How familiar were you with the iPad^{TM} we asked you to use^{TM}?" (measured on a 5-point Likert-type scale with anchors ranging from "Not at all familiar" to "Completely familiar"), "How interesting did you find the iPad^{TM}?" (measured on a 5-point Likert-type scale with anchors ranging from "Not at all interesting" to "Very interesting"), and "With respect to ease of use, how would you rate the iPad^{TM}?" (measured on a 5-point Likert-type scale with anchors ranging from "Very difficult to use" to "Very easy to use").

Parents also rated children's response to the iPad^{TM} used during the observational setting through three questions including, "How do you think your child responded to the iPad^{TM}?" (measured on a 5-point Likert-type scale with anchors ranging from "Did not like it at all" to "Liked it a lot"), "How would you rate your child's familiarity with the iPad^{TM} we asked you to use?" (measured on a 5-point Likert-type scale with anchors ranging from "Not at all familiar" to "Completely familiar"), and "How would you rate your child's interest with respect to the iPad^{TM} we asked you to use?" (measured on a 5-point Likert-type scale with anchors ranging from "Uninterested" to "Very interested").

Procedures

Recruitment advertisements appealed to mothers and fathers with children between 2 and 6 years of age. Parents were informed that the study "examines how children use technology and parent perceptions about technology use." Flyers provided an email contact address for interested parents. Parents had the option of completing the pre-observation survey either online or via hard-copy. Some parents completed the survey at home while others completed it on site at the university developmental psychology research lab. Research assistants supervised children for parents who completed the survey on site. The observation session began by welcoming parents into the observation room. The room was organized to reflect a "home" environment with a loveseat, two child-sized tables with two chairs and a large oval alphabet carpet to cover the floor. A brief overview was provided for parents to introduce them to navigation (opening and closing applications, movement within applications, orientation of the device in portrait and landscape mode, volume control buttons, home button to exit applications, and the various menus consisting of default apps and downloaded games), the functions available on the iPad^{TM} and the 12 applications downloaded onto the iPad^{TM}. Parent–child dyads were given the iPad^{TM} turned on and set at a comfortable volume level and were free to select from the 12 applications as well as typical applications/functions that appear on most iPads^{TM} (e.g., photo album, camera, music, etc.). Parents were reminded that the purpose of the observations was to better understand how technologies are typically used within the home and parents were encouraged to do what they normally would do with their child. Parent–child dyads were given 10 min to play with the iPad^{TM}. Typically two research assistants were involved in each testing session. One research assistant was always present in the observation room to assist with the mobile device or answer questions. This research assistant was seated in a far corner and was instructed to be engaged in other activities (not watching, or making eye contact) except when a parent requested assistance. This research assistant also indicated when the 10 min observation time was completed. Following the observation session, parents were asked to complete the short post-observation survey.

RESULTS

Introducing Technology to Children

Parents were asked to indicate the age at which they would consider introducing digital technologies to their children using one of the 12 options encompassing 6 month intervals from birth to 6 years (see **Table 1**). Interestingly 17.5% of parents supported introducing technology in the first year of life. Similarly, the greatest proportion of parents supported introducing technology early with almost a quarter of all parents supporting 1.5–2 years of age (24.3%) and another 19.4% supporting 2–2.5 years of age. Fewer than 10% of parents supported school age or later as the ideal time for introduction. ANOVAs indicated no significant differences in preferred age of introduction between mothers and fathers, $F(1,101) = 0.01$, $p = 0.91$[1] . However, parents with less familiarity ($M = 6.00$, $SD = 3.48$,) with technology (non-users) indicated a much later age for introduction (3–3.5 years of age) in comparison to users ($M = 4.37$, $SD = 2.48$, reflecting ages between the 2–2.5 and 2.5–3 years categories), $F(1,101) = 6.65$, $p = 0.01$, $\eta^2 = 0.06$, and $t(102) = 2.58$, $p = 0.01$.

Parents were asked two questions regarding access to technology. First, over 80% of parents indicated that their children were permitted access to digital technologies. Interestingly, over 94% of these parents allowed access to mobile devices such as the iPad^{TM} used in the present study. Among parents who permitted access to technology, ANOVAs indicated that access to devices such as the iPad^{TM} did not differ as a function of parental gender or technology experience, $F(1,84) = 1.465$, $p = 0.23$ and $F(1,84) = 0.73$, $p = 0.40$, respectively. Further, 80% of these parents indicated that they download applications for their children. Downloading applications did not differ as a function of parental gender or technology experience.

To better understand why parents decide to provide children with access to technology, parents were asked to identify the rationale(s) that supported their decision from a list of 15 possible choices (parents could indicate as many as were appropriate; see **Table 2**). A wide range of rationales were selected with most parents endorsing multiple rationales. Although fun or entertainment was the most highly endorsed rationale (56.7%), several educational goals were also frequently endorsed including promoting development in; problem-solving (53.8%), basic math (53.8%), reading (51%), language (47.1%), and science (26%) as well as building hand-eye coordination (46.2%). The least endorsed rationales included: searching for information (12.5%), learning about history (9.6%) and building social skills (4.8%). Comparisons between mothers and fathers did not yield significant differences among the rationales identified. Chi square analyses were conducted for 11 rationales with sufficient sample size to permit comparisons as a function of technology experience. Given the number of comparisons, a corrected $p = 0.004$ was used. Three comparisons were statistically significant. A greater proportion of parents with technology experience endorsed 'developing basic skills in math,' χ^2 (1, $N = 104$) = 8.85, $p = 0.003$, 'developing basic skills in reading,' χ^2 (1, $N = 104$) = 9.57, $p = 0.002$, and 'fun/entertainment,' χ^2 (1, $N = 104$) = 8.20, $p = 0.004$ as important for introducing technology. In addition there was a strong trend supporting 'developing basic skills in language,' χ^2 (1, $N = 104$) = 7.06, $p = 0.008$ as an additional rationale endorsed by parents with greater technology experience.

Scaffolding Children during Mobile Technology Play

Three raters worked collaboratively on video files for four observation sessions to identify the types of scaffolding parents offered to their children during the interactive play session with the iPad^{TM}. Raters reached consensus in identifying scaffolds. Four types of support were identified: physical, verbal, emotional-verbal, and emotional-physical, plus two additional categories were coded, distractors and off-task behavior. The three raters then independently coded 20% of the video-recorded observation sessions for these categories. Agreement between pairs of raters (raters 1 and 2 and raters 2 and 3) was calculated with high overall inter-rater agreement exceeding 92% for each comparison.

Physical supports included holding or adjusting the iPad^{TM} for the child to use, pointing to the screen (both in general and to a specific location), touching (pressing) the screen for the child, and helping the child point to something by a hand-over-hand method.

Verbal supports included repetition or clarification of the game instructions, reading aloud something written on the tablet screen (e.g., "so that says, 'Jack played a ___.'"); providing hints and examples (e.g., "'A,' like 'apple.'"), providing direct/step-by-step instruction (e.g., "now press on the green 'play' button."), asking direct or indirect questions (e.g., "where is the number seven?" and "can you tell me where the triangle is?"), commenting or acknowledging something on the screen (e.g., "look at that, you got three stars"), telling the child to try again (e.g., "try that again."), and providing the child with corrective statements indicating that they are doing something wrong (e.g., "oops," "uh-oh").

Emotional-verbal supports consisted of verbal prompts that contained an emotional element including: praise, encouragement (e.g., "you can do it," "there you go!" "yes,

[1]Separate ANOVA and MANOVA analyses were conducted to examine technology experience and gender differences to accommodate the smaller sample size of non-users.

TABLE 1 | Percentage of parents endorsing each age group at which they would introduce technologies to their children.

Age range provided	Gender		Experience		Total
	Male	Female	User	Non-user	
1. Birth – 6 months	6.3%	2.8%	5.1%	0	3.9%
2. Just over 6 months to 1 year	12.5%	13.9%	13.9%	12%	13.6%
3. Just over 1.5–2 years	25%	23.6%	25.3%	20%	24.3%
4. Just over 2–2.5 years	15.6%	20.8%	19%	20%	19.4%
5. Just over 2.5–3 years	9.4%	9.7%	10.1%	8%	9.7%
6. Just over 3–3.5 years	15.6%	5.6%	11.4%	0	8.7%
7. Just over 3.5–4 years	0	4.2%	3.8%	0	2.9%
8. Just over 4–4.5 years	3.1%	5.6%	3.8%	8%	4.9%
9. Just over 4.5–5 years	0	4.2%	0	12%	2.9%
10. Just over 5–5.5 years	6.3%	2.8%	2.5%	8%	3.9%
11. Just over 5.5–6 years	0	0	0	0	0
12. After 6 years of age	6.3%	5.6%	3.8%	12%	5.8%

TABLE 2 | Rationales for introducing children to technology.

	Gender		Experience		Total
	Male	Female	User	Non-user	***N* = 104**
Building hand–eye coordination	56.3%	41.7%	53.2%	24%	46.2%
Strengthening reflexes	25%	23.6%	24.1%	24%	24%
Building social skills	9.4%	9.7%	10.1%	8%	9.6%
Building problem-solving skills	56.3%	52.8%	60.8%	32%	53.8%
Developing basic skills in math	56.3%	52.8%	62%	28%	53.8%
Developing basic skills in reading	56.3%	48.6%	9.5%	24%	51%
Developing basic skills in language	53.1%	44.4%	54.4%	24%	47.1%
Developing basic skills in science	28.1%	25%	29.1%	16%	26%
Arts and Crafts	43.8%	26.4%	38%	12%	31.7%
History	6.3%	4.2%	3.8%	8%	4.8%
Searching for information	12.5%	12.5%	12.7%	12%	12.5%
Fun/Entertainment	59.4%	55.6%	64.6%	32%	56.7%
Developing skills for future school success	34.4%	41.7%	44.3%	24%	39.4%
Occupying your child	50%	43.1%	51.9%	24%	45.2%
My child asked for it	18.8%	26.4%	25.3%	20%	24%

that's right,"), creating excitement and emotion through sound effects, gasps, and other vocalizations (e.g., "ooh," "woah!"), and laughing (i.e., creating a positive mood).

Emotional-physical supports were identified as physical supports with an emotional element including: touching the child (e.g., scratching or ruffling their hair, patting them on the back), physical expressions of praise (e.g., high-five, thumbs-up), shaking the child by the shoulders/their hand when they successfully accomplished something, kissing the child, facial expressions (e.g., smile, frown, grimace, shudder), nodding or shaking their head to indicate approval or disapproval, and cuddling with the child or hugging the child.

Two additional categories (Distracted and Off task) were coded to accommodate momentary off-task behaviors and more sustained off-task behaviors of parents but so few of either category were observed that these categories were not included in any analyses.

A time sampling technique was used to code events in the observation session. Each 10-s interval of the 10-min observation session was sampled for the four types of scaffolding. Interestingly, parents provided a great deal of support to their child in the 10-min session. On average 79 ($SD = 36.27$) verbal supports, 76 ($SD = 51.83$) physical supports, 23 ($SD = 14.40$) emotional-verbal supports, and 6 ($SD = 9.53$) emotional-physical supports were provided during the 10 min sessions (see **Table 3**).

Correlations among these four types of scaffolding were conducted (see **Table 4**). Verbal scaffolding was significantly correlated with emotional-verbal scaffolding and physical scaffolding, $r = 0.465$, $p < 0.01$ and $r = 0.554$, $p < 0.01$, respectively. Emotional-verbal scaffolding also was correlated with emotional-physical scaffolding, $r = 0.22$, $p < 0.05$. No other correlations were significant.

Two MANOVAs were conducted to examine whether users and non-users or mothers and father differed in the types

TABLE 3 | Mean number of instances for each scaffolding type during 10-min iPad™ observation session.

	Gender		Experience		Total
	Male	Female	User	Non-user	$N = 102$
Scaffolding type	M (SD)	M (SD)	M (SD)	M (SD)	M (SD)
Physical supports	75.77 (58.82)	76.69 (48.93)	74.53 (53.29)	82.54 (47.32)	76.41 (51.83)
Verbal supports	80.90 (35.32)	78.31 (36.89)	80.19 (37.23)	75.54 (33.43)	79.10 (36.27)
Emotional-verbal supports	22.71 (16.08)	22.76 (13.72)	21.31 (12.54)	27.42 (18.81)	22.75 (14.40)
Emotional-physical supports	3.90 (4.66)	6.61 (10.93)	5.82 (10.53)	5.67 (5.24)	5.78 (9.53)
Distractor	0.48 (1.29)	0.72 (1.42)	0.59 (1.22)	0.83 (1.81)	0.65 (1.38)
Off-task	0.55 (1.06)	0.83 (3.45)	0.41 (1.05)	1.83 (5.69)	0.75 (2.93)

of supports they offered their child. Although there were no statistically significant differences between users and non-users for the four scaffolding measures, the emotional-verbal comparison approached significance, $F(1,102) = 3.14$, $p = 0.08$, $\eta^2 = 0.03$. Exploration of this trend suggests that non-users engaged in more emotional-verbal supports ($M = 27.42$, $SD = 18.81$) than users ($M = 21.58$, $SD = 12.37$) in the 10-min iPad™ observation session. There were no significant differences between mothers and fathers on any of these four scaffolding measures, with the largest value being for emotional-physical scaffolding, $F(1,102) = 1.76$, $p = 0.18$.

Engagement by Children

Scoring of the videos also revealed that children were occasionally off-task or unengaged with the iPad™ activity. Two raters reviewed all observation videos and recorded the total number of times children were off-task as well as the duration of each instance that the child was not engaged. A total time off-task score was calculated by adding all individual off-task periods. Children varied in the number of off-task events with the average number of times off-task being less than two times (range = 0–15 instances; $M = 1.37$, $SD = 2.80$). The average of each instance spent off-task was approximately 13 s ($M = 12.88$, $SD = 31.11$). The duration ranged from 0 to 158.86 s with two outliers of 304.07 and 311.44 s that were greater than 3 standard deviations from the mean. Given these outliers, the previous observational data and subsequent analyses using observational data were re-analyzed without the two outlier children's scores. No differences in outcomes were noted when these children were added or deleted from the calculations. All data reported in the present results section has these two children's data deleted from assessments involving the observations. Overall, assessment of children's off-task behaviors indicated that children spent the vast majority of the time engaged with the technology and if they were not engaged, it was for a short duration.

TABLE 4 | Correlations among the types of parental scaffolding (i.e., verbal, emotional-verbal, physical, and emotional-physical) provided during the parent–child tablet play session.

	1	2	3	4
1. Verbal scale	–	–	–	–
2. Emotional-verbal scale	0.457**	–	–	–
3. Physical scale	0.556**	0.193	–	–
4. Emotional-physical scale	0.099	0.210*	0.081	–

**$p < 0.01$ (2-tailed), *$p < 0.05$ (2-tailed).

Variables Impacting on Scaffolding

To explore whether individual characteristics of parents or children influenced the amount of scaffolding provided, four regression analyses were conducted, one for each of the four types of scaffolding. In all cases the type of scaffolding served as the dependent variable and child age, child gender, parent age, parent gender, and parent experience (user/non-user) served as the predictor variables.

The overall models for verbal scaffolding, $F(5,101) = 8.09$, $p < 0.001$, $R^2 = 0.30$, and physical scaffolding, $F(5,101) = 6.07$, $p < 0.001$, $R^2 = 0.24$, were statistically significant. Both verbal and physical scaffolding were predicted by child age, $\beta = -1.44$, $r = -0.53$, $t(101) = -6.2$, $p < 0.001$; $\beta = -1.81$, $r = -0.47$, $t(101) = -5.27$, $p < 0.001$, respectively, and parent age, $\beta = 1.44$, $r = 0.19$, $t(101) = 2.21$, $p = 0.03$; $\beta = 2.57$, $r = 0.23$, $t(101) = 2.61$, $p = 0.01$, respectively. As child age increased, the amount of verbal and physical scaffolding parents provided their children decreased. In addition, older parents provided more verbal and physical supports than younger parents.

With respect to the two emotionally based scaffolding supports, neither model was significant.

Parental Perceptions of the iPad™ Observation Sessions

Parents indicated a moderately high level of interest in the iPad™ device ($M = 3.85$, $SD = 0.91$) and found it relatively easy to use ($M = 3.85$, $SD = 0.91$). When mothers and fathers, and users and non-users, were compared, they did not differ in their ratings of interest or ease of use. A comparison of mothers' and fathers' ratings of familiarity with the iPad™ revealed that mothers ($M = 3.31$, $SD = 1.39$) felt less familiar with the device than fathers ($M = 3.91$, $SD = 1.40$), $t(102) = 2.03$, $p = 0.045$. As expected, users ($M = 3.90$, $SD = 1.27$) reported greater familiarity with the iPad™ than non-users ($M = 2.20$, $SD = 1.04$), $t(102) = 6.08$, $p < 0.001$.

Parents were also asked to rate their child's interest and familiarity with the iPad™ and how much they thought the child liked using it. Four parents did not respond to the interest and liking scales and five parents omitted the familiarity question. Overall, mean interest scores indicated that children were perceived to be very interested in the iPad™ ($M = 4.46$, $SD = 0.79$). Similarly, children were perceived to be very positive about using the iPad™ with mean ratings close to the highest level ($M = 4.34$, $SD = 0.78$) on the 5-point Likert-type scale (5 = "Liked it a lot"). Ratings were also positive, although slightly lower for familiarity with the iPad™ ($M = 3.21$, $SD = 1.3$). Comparisons between mothers and fathers, and users and non-users, revealed no significant differences in ratings. Four regression analyses were conducted to determine if parental perceptions regarding their child's responsiveness, interest and familiarity with the iPad™ predicted the type of scaffolds they provided (physical, verbal, emotional-physical, emotional-verbal). Three of the four models were significant; Physical [$F(3,96) = 6.10$, $p < 0.001$, $R^2 = 0.16$], Emotional-Physical [$F(3,96) = 4.73$, $p < 0.004$, $R^2 = 0.13$], Emotional-Verbal [$F(3,96) = 7.25$, $p < 0.001$, $R^2 = 0.19$]. The model for Verbal scaffolding approached significance [$F(3,97) = 2.44$, $p = 0.07$, $R^2 = 0.07$]. In each case higher perceived child familiarity with the iPad™ predicted less scaffolding, Emotional-Physical $\beta = -0.395$, $r = -0.34$, $t(96) = -3.54$, $p < 0.001$; Physical $\beta = -0.338$, $r = -0.29$, $t(96) = -3.09$, $p < 0.003$; Emotional-Verbal $\beta = -0.380$, $r = 0.33$, $t(96) = -3.53$, $p < 0.001$; Verbal $\beta = -0.30$, $r = -0.26$, $t(97) = -2.63$, $p = 0.010$ scaffolding. In addition, higher perceived responsiveness of the child predicted more Emotional-Verbal scaffolding $\beta = 0.357$, $r = 0.22$, $t(96) = 2.38$, $p < 0.019$.

Finally, parents were asked to report how similar the interactive iPad™ session was to the typical interactions they have at home with their child involving technology. Overall, parents indicated that the session was quite similar to the typical interactions they have with their child involving technology ($M = 3.62$, $SD = 1.06$). No significant differences were found between mothers and fathers and users and non-users.

DISCUSSION

The two primary goals of the present study were to understand parental perceptions toward introducing mobile technologies to children and to directly observe shared parent–child computer experiences while engaged with an iPad™ to determine if and then how parents use scaffolding with their young children. A growing body of literature from popular media and survey studies suggests that since mobile technologies have become a ubiquitous presence in today's society, earlier exposure in child populations is becoming more common (e.g., Rideout, 2013; Kabali et al., 2015). The results of the present study confirm parental support for early exposure. Only 9.7% of parents advocated for school-age as the time for introduction. Instead, 43% of parents indicated introduction during infancy (6 months to 2 years) and the majority of parents (61%) supported introduction before 2.5 years of age. There are two important implications that follow from these outcomes. First, early exposure, as noted here, clearly challenges the recommended guidelines regarding screen exposure that is currently advocated by the American Academy of Pediatrics (2001, 2015) that "television and other entertainment media should be avoided for infants and children under age 2. (2015)" The second implication is that parents and family contexts will be the most likely environments in which children gain initial exposure to and use of technologies.

The lack of agreement between what parents believe is good practice regarding the introduction of mobile technologies and what experts in early development indicate as appropriate could signal a potential problem for children developmentally. Specifically, early exposure may limit valuable learning experiences consistent with the deficits identified with passive television viewing (e.g., Napier, 2014) by limiting opportunities to interact with live individuals and limiting active engagement with manipulatives, toys, and the larger environment. Alternatively, it may be the case that developments in the design of software and hardware may have surpassed perceived limitations and could now permit a more active and enriched experience for young children. Although no data are available for infants (aged two and under), a growing body of research supports both learning gains and positive social outcomes when young children use well-designed instructional software (e.g., Willoughby et al., 2009; McKenney and Voogt, 2010; Murray and Olcese, 2011; Tamim et al., 2011; Savage et al., 2013). In addition, the size and flexibility afforded by small mobile technologies such as touchscreen tablets extends children's learning environments by permitting engagement in multiple contexts rather than the constrained, and perhaps more intentional opportunities associated with desktop computer use.

Interestingly, the age of introduction to technology was influenced by technology experience among parents, with non-users supporting a slightly later introduction age than users. It is not surprising that experienced users would be more likely to introduce the technology to their child as they would be more likely to have opportunities for introduction while using the technology themselves. Even among the non-users, however, the average age of introduction was in the early preschool years (i.e., 3–3.5 years of age). Overall, both the sample in general, and experienced users in particular are likely to invite children to engage with mobile technologies early in development. Thus, understanding the entirety of the parent–child-technology triad becomes a necessity.

The present study indicates that in the best case situation, when being observed, while interacting with their child and technology, parents are engaged. They employ diverse scaffolds to encourage and support their child, and they are positive in their interactions. Parents were observed providing four different types of scaffolding in the interactive iPad™ sessions (i.e., verbal, physical, emotional-verbal, and emotional-physical). Specifically, in the 10-min time span 79 verbal supports and 76 physical supports were offered indicating an average of over 7 of each of these scaffolds per minute. Emotional supports (i.e., emotional-verbal and emotional-physical) were offered less frequently but nonetheless were relatively prominent within the interactions with emotional-verbal supports appearing more frequently than emotional-physical supports. Clearly, parents were actively providing their children with verbal supports to help children understand content, physical supports to aid in manipulating the device and navigating the software, emotional-verbal supports to offer encouragement and praise and emotional-physical supports to acknowledge the child's successes (e.g., high-five for a job well done).

Neither experience with technology nor gender was predictive of differences in scaffolding. The consistency across genders and users and non-users suggests that features specific to the child or other environmental constraints are responsible for differences in the types of scaffolds parents provide their children. Indeed, with respect to verbal and physical scaffolding, both the child's age and parental age predicted the amount of scaffolding parents provided their child such that as the age of the child increased, the amount of scaffolding decreased. Importantly, this finding suggests that parents were reducing scaffolding consistent with expected developmental gains in their children's capabilities, reflecting sensitive scaffolding on the part of parents. Effective scaffolding presumes that supports are tailored to the needs of the learner and this appears to be evident in the present study.

Interestingly, older parents provided more verbal and physical supports than younger parents in the interactive iPad^{TM} session. Existing literature suggests that older parents are more likely to show and feel less stress in their parenting efforts, use better coping strategies and provide more positive reinforcement than younger parents (Auyeung et al., 2011). The current findings suggest these behaviors may translate into more scaffolding in the mobile technology context, perhaps through more graduated scaffolding. Older parents may have persisted longer with verbal and physical supports to fully ensure and reinforce their children's skill acquisition.

None of the individual characteristic variables that were collected (i.e., child age, child gender, parent age, parent gender, and parental experience) predicted emotional-verbal and emotional-physical scaffolding for the interactive iPad^{TM} session. All sessions were positive. It may be that parents provide emotional supports – both in verbal form such as praise and encouragement and in physical form such as smiles and hugs – naturally as a means to encourage ongoing exploration and engagement. One extension to the current research would be to explore the frequency with which parents shifted across programs and the duration that parents encouraged for particular games, especially those which were either minimally challenging or highly challenging for their child. In the present study, parents could select activities and shift among activities but we did not track specific programs used. Challenges inherent in the software may have an impact on the amount and type of emotional scaffolds required. Further investigation of these emotional supports would be desirable especially as a function of task difficulty where more or fewer supports may be required for effective scaffolding.

Parents demonstrated a desire to support their children's learning and identified mobile technologies as a platform for achieving educational and entertainment goals. Among those parents (80%) who indicated that they specifically download applications for their children, the majority did so to provide their child with a fun and entertaining experience. This consistency in response indicates that parents believe mobile technologies afford engaging experiences for their children. Several researchers have identified high engagement as a product of children's software and computers in general (e.g., Willoughby and Wood, 2008). In addition to entertainment, many parents endorsed developing foundational academic skills (i.e., literacy, numeracy) and basic proficiency skills (i.e., hand–eye coordination) as key goals. Neither gender of the parent nor experience with technology discriminated among these rationales. Overall, parents perceive important potential learning outcomes when downloading applications for their young child to use, which is consistent with extant literature associated with quality program design (Grant et al., 2012).

Parental Attitudes toward the Touchscreen Tablets

Overall, parent's ratings of the iPad^{TM} technology were generally positive. Perceived interest and ease of use did not differ between mothers and fathers or users and non-users. However, mothers rated themselves less familiar with the technology than fathers. Although gender differences were not expected, they are consistent with some studies indicating that women generally perceive themselves as being less familiar with technologies than men (e.g., Venkatesh et al., 2000) even though actual use or skills may not differ. Consistent with expectations, parents experienced in using mobile technologies reported higher ratings of familiarity.

Parents were also asked to rate how their child responded to the devices used in the present study. Responses were positive. Parents perceived iPad^{TM} play to be engaging for their child. There were no differences between mothers' and fathers' ratings or users' and non-users' ratings. Parents also rated their child's familiarity with the device and a comparison of mothers and fathers did not reveal any differences. However, users reported their child as being more familiar with the device than non-users. This may be due to increased exposure to similar mobile devices at home for children of parents who are users. This perceived familiarity among users, however, did not appear to influence the actual scaffolding provided during the observation. It may be that parents who are more familiar with these technologies have generally higher perceptions of familiarity overall but when they engage with their children they scaffold according to the child's needs rather than perceived skills. With respect to parental ratings of their child's interest in the iPad^{TM}, interest was perceived to be high and there were no differences as a function of technology experience.

Fidelity within the Study

Several measures were used to ensure that the methods and assumptions involved in the design of the study were evident in the outcomes. Parents' ratings of the similarity of the observation session to typical interactions they have at home with their child involving technology revealed no differences between mothers and fathers and users and non-users. Importantly, this measure served as a fidelity measure for the observation sessions as parents generally indicated that the sessions reflected their experiences at home rather than a unique experience specific to the lab setting. This was a positive outcome as the study sought to imitate the 'home' environment as much as possible. An important next step would be to explicitly examine parent child interactions in the home and perhaps over an extended time frame to more confidently map 'typical' and "ideal" behaviors.

Limitations and Future Directions

One notable limitation in the present study was the small number of non-users relative to users of technology. Recruiting non-users was a challenge. This is perhaps not surprising given the age of the vast majority of the parents in the present study. These parents would fall within the group identified as 'digital natives'- those who have grown up with technology (Prensky, 2001). Perhaps it was more surprising that 25 non-users were found rather than none. However, the limited number of non-users warrants caution when interpreting the user versus non-user outcomes.

The present study did not include demographic information related to ethnicity and socio-economic status (SES) of participants. However, parental educational level suggests that the current sample was more highly educated than the general population. These factors could potentially play an important role in the way parents interact with their child when using a mobile device, given the increasing use of mobile technologies especially in lower SES groups (Kabali et al., 2015). In addition, future research should consider the relative engagement afforded to mobile technologies versus other important learning opportunities (e.g., shared reading, manipulative play) and the decisions that parents make regarding how they should support their children in these different contexts in order to fully understand how parents allocate support and scaffolding for their children's learning.

Conclusion

The present study explored first-hand the nature of the parent–child interactions that take place when children and parents engage in shared-computer activities using a mobile device. The results and implications of this study are important for parents, educators, and childcare providers. Most notably, these parents were very involved and interactive with their child when using the touchscreen tablet. Being an active contributor to children's learning by providing them with verbal, physical, and emotional support is beneficial, allowing children to engage more actively in the learning tasks through the assistance of a more skilled adult. A second important finding suggests that early introduction to technology is the expectation among parents today, indicating the need to examine very early exposure both in terms of parental support and child learning outcomes. The present study extends the existing literature by examining informal learning contexts between parents and children to see how instruction and support is handled. Gaining an insight into the fundamental behavioral exchanges that occur between parent and child when using mobile technologies may help in understanding how to better support parents and how to support children who have early experiences with technologies. Given positive evidence of the potential for computer assisted instruction in informal learning contexts (Korat and Or, 2010), the present study also provides a foundation for encouraging attention to software development for children, especially very young users. It also suggests to software designers the importance of developing informative and engaging parent portals to support parents who will be scaffolding technology use for their young children.

AUTHOR CONTRIBUTIONS

EW and MP participated in each phase of the study from design to the final manuscript. AG contributed significantly to design analyses and writing. DDP contributed significantly to recruitment, data collection and design. RS and MAE contributed to research design and theoretical development.

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