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ToyMatch: a temperament-aligned toy recommendation system for circular design in early childhoods

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Introduction: Toy consumption during early childhood presents a critical opportunity to integrate child temperament, sustainable toy design, and value-aligned decision-making into everyday caregiving. Yet most existing recommendation systems focus on age or gender, neglecting emotional durability, caregiver sustainability priorities, and the potential of circular consumption informed by transdisciplinary methods.

Methods: This study introduces ToyMatch, a multi-layered toy recommendation system that integrates psychological profiling (based on the ICID-FFM model), behaviorally defined toy design features, and value-based filters derived from a prior Analytic Hierarchy Process study with 220 caregivers in Türkiye. The system was empirically tested with a separate sample of 214 Turkish caregivers of 3- to 6-year-old children. Clustering, regression, and SHAP-based analyses were conducted to evaluate alignment between temperament traits, design features, and toy preferences.

Results: Results showed meaningful matching patterns for Extraversion, Conscientiousness, and Openness traits, while Agreeableness and Neuroticism remained less predictive.

Discussion/conclusion: A mobile interface prototype was proposed to operationalize the recommendation process through a low-input, stereotype-neutral structure. Although emotional durability and long-term behavioral impact were not directly measured, the findings suggest that temperament-aligned, value-embedded toy design can promote longer engagement and more sustainable consumption habits. By encouraging developmentally attuned and emotionally resonant toy use, ToyMatch contributes a speculative but actionable model for cultivating circular mindsets in early childhood design and caregiving practices.

KEYWORDS

child temperament, sustainable toy design, emotional durability, circular consumption, recommendation systems, value-aligned design, caregiver sustainability priorities, transdisciplinary methods

1 Introduction

In the face of planetary crises and escalating ecological precarity, that sustainable transitions must be rooted not only in technical innovation but also in cultural transformation (Gajparia et al., 2022; Wahlen and Stroude, 2023). This includes rethinking the values, behaviors, and material engagements that shape early patterns of consumption

and meaning-making. Children's toys, often dismissed as trivial or fleeting, represent a powerful and underexplored domain where such transformation can begin. By emphasizing emotional durability, developmental fit, and sustained user engagement, toys can become formative tools for cultivating sustainability mindset from, early childhood (Halli et al., under review¹; Lukman et al., 2021; Özkürkçü, 2024).

Emerging evidence shows that, caregivers likewise prioritize educational benefits, adaptability to developmental change, and the depth of emotional connection over environmental labels alone (Al Kurdi, 2017; Fisher et al., 2008; Halli et al., 2023; Richards et al., 2020). Yet, current toy classification and recommendation systems remain limited, relying on simplistic categories such as, age, gender, or broad educational, functions, overlooking children's psychological diversity and caregivers' sustainability priorities (Halli et al., 2023; Levesque et al., 2022; Lukman et al., 2021). However, unlike domains such as film or music where recommender systems benefit from rich behavioral data, toy recommendation tools remain restricted to static factors, leaving a critical gap in addressing emotional durability and developmental fit. Even emerging AI-driven recommendation models tend to optimize predictive accuracy rather than embedding psychological interpretability or value-informed sustainability dimensions (Zangerle and Bauer, 2023). This leaves a gap that ToyMatch explicitly addresses, enabling toys to better foster long-term engagement, emotional attachment, and more reflective consumption practices. This paper addresses this gap by proposing a multi-layered toy recommendation framework, ToyMatch, as a vehicle for cultivating regenerative mindsets and emotionally durable engagements in early childhood. Rather than restricting sustainability to material attributes such as biodegradability or recyclability, the framework emphasizes emotional resonance, developmental fit, and caregiver-defined values. These elements together can extend toy lifecycles, reduce premature disposal, and, advance the cultural foundations of a circular society. While previous research has framed early childhood education as a site for developing sustainability mindsets (e.g., Kosta et al., 2022; Tsironis et al., 2024b), ToyMatch operationalizes this vision through a design-based system that connects psychological traits, toy aesthetics, and caregiver values.

The ToyMatch framework integrates three interdependent layers:

- i. Children's temperament traits, based on the Inventory of Children's Individual Differences (ICID) short form adapted to the Five Factor Model (FFM) and translated into ToyMatch behavioral personas (Halli and Kaya, under review)²,
- ii. Toy design features, categorized into 76 binary-coded behavioral attributes,

- iii. Turkish caregiver-defined sustainability values, derived through Analytic Hierarchy Process (AHP) methods (Halli et al., 2023).

Although grounded primarily in behavioral psychology and design science, the framework is also informed by perspectives from Social Sciences, Arts, and Humanities (SAH), particularly in addressing ethical, cultural, and symbolic dimensions of play (Callmer and Boström, 2024; Delaney and Liu, 2023). Normative filters inspired by SAH help avoid reinforcing harmful stereotypes or recommending aggressive content instead prioritizing inclusivity, non-violence, and gender-neutrality (Gajparia et al., 2022). To ground this framework empirically, we tested it with 214 caregivers in Türkiye and piloted a mobile prototype, providing initial insights into how psychological traits, toy features, and caregiver values intersect.

By situating toy selection within a broader ecosystem of psychological relevance, value-informed decision-making, and sustainable design, ToyMatch is framed not only as a recommendation system but as a speculative prototype for cultural change. It invites caregivers, educators, designers, manufacturers and policymakers to co-create circular imaginaries rooted in empathy, adaptability, and intergenerational care. By linking psychological dimensions to toy design features and embedding these within a value-informed decision process, the system moves beyond personalization with the potential to function as a transformative tool in caregiver decision-making. In doing so, it supports circular economy goals by fostering emotional durability, reducing premature disposal, and minimizing material waste. The aim is not only to match children with more engaging toys, but to encourage more conscious design practices, value-aware parenting, and emotionally intelligent consumption cultures, repositioning early childhood consumption as a formative site for circular futures. The remainder of the article situates ToyMatch at the intersection of sustainable toy design, temperament-informed personalization, and value-based classification (Section 2), details the framework's three layers (Section 3), presents empirical analyses with Turkish caregivers (Section 4), and discusses implications for transformative mindsets and circular consumption (Section 5).

2 Literature review

This section offers a focused literature review structured around four key themes. The first part, "Reframing sustainability in toy consumption: from materials to meaning", traces the shift from material-based to meaning-centered approaches in sustainable toy use. The second, "Temperament as a design-relevant lens", highlights the ICID framework as a psychological tool to align design with individual child traits. The third, "Feature-based toy classification", examines how toy attributes can be organized around behavioral compatibility rather than conventional categories. Finally, the fourth part, "Critical perspectives on recommendation models for children", reviews current recommender systems and outlines their key shortcomings in capturing emotional durability, interpretability, and sustainability, setting the stage for ToyMatch's multi-layered

¹ Halli, S., Kaya, C., and Kucuksayrac, E. (under review). *Emotionally durable toys and caregiver decision-making: play engagement in Turkish families*.

² Halli, S., and Kaya, C. (under review). Temperament-based toy design for preschoolers: a persona profiling method for cleaner production and consumption through emotional durability.

design. Together, these themes provide the conceptual foundation for the ToyMatch system.

2.1 Reframing sustainability in toy consumption: from materials to meaning

Toys are not only tools for play but also carriers of emotional, cognitive, and ecological narratives that shape how young people relate to objects, others, and the world (Cetin Dag et al., 2020; Healey et al., 2019). Although children are rarely included as agents in sustainability conversations, their daily interactions with designed objects actively shape emerging worldviews (Percy-Smith and Burns, 2013). In this context, circularity should not be viewed solely through the lens of material loops, such as recovery, resale, or reuse (Hussain et al., 2025), but also through the lens of behavioral continuity (Colley et al., 2024). Recent work suggests that both environmental knowledge and emotional connectedness can be cultivated from an early age, forming the basis for later sustainability behaviors and value-driven choices (Kosta et al., 2022, 2025).

Traditional discourses around sustainability in product design often prioritize material durability, recyclability, and eco-efficiency (Levesque et al., 2022; Lukman et al., 2021; Robertson and Klimas, 2019). In the toy industry, such perspectives have led to a focus on wooden toys, modularity, or non-toxic materials (Choi et al., 1997; Scherer et al., 2017). However, these material dimensions alone cannot ensure long-term use, emotional attachment, or ethical consumption practices, particularly in early childhood.

Emerging scholarship (Al Kurdi, 2017; Healey et al., 2019; Richards et al., 2020) suggests that developmental relevance, emotional resonance, and adaptive growth potential are more impactful predictors of sustainable use than physical durability alone. For instance, a survey of 220 Turkish caregivers using AHP found that values such as educational utility, enjoyment, and growth adaptability carried significantly more weight than traditional eco-indicators like reusability or biodegradability (Halli et al., 2023). Similar findings have been reported in other studies, which highlight how toy choices are often shaped by cultural expectations of academic preparedness, gender norms, and parental aspirations (Kagıtcıbası, 2017; OECD, 2023; Özkürkçü and Doğan, 2025).

This shift from material performance to value-based sustainability aligns with a broader rethinking of circularity, not as a technical loop, but as a regenerative cultural system grounded in care, learning, and long-term relationality (Kaszynska, 2025). In this light, sustainable toy consumption becomes a site for cultivating transformative mindsets, where caregivers and children co-construct narratives of value and attachment, resonating with perspectives from cultural studies and the arts, challenging the dominant linear logic of use and discard.

2.2 Temperament as a design-relevant lens: the ICID framework

Temperament traits offer a powerful but underutilized lens through which to design emotionally and developmentally

appropriate objects (Hong et al., 2024). Rooted in biological and psychological research, temperament captures individual differences in reactivity, sociability, attentional focus, and self-regulation (Li et al., 2011; Rothbart et al., 2001). These traits begin to manifest as early as age 1.5 and shape not only play preferences but also emotional bonding, frustration tolerance, and imaginative engagement, which are essential for socio-emotional development and symbolic play (Denissen et al., 2013; Li et al., 2014; Rothbart et al., 2001).

Tools like ICID adapt FFM for use in early childhood³, allowing for concise yet meaningful profiling of personality dimensions such as Openness, Conscientiousness, and Extraversion (De Fruyt and Karevold, 2021). In the context of design, temperament data has been shown to predict which toy features support longer play, deeper attachment, and reduced toy abandonment (Halli et al., under review¹; Özkürkçü, 2024). By translating these traits into design-responsive personas, the ICID framework helps bridge the gap between abstract behavioral tendencies and concrete design parameters (Halli and Kaya, under review²). For example, highly conscientious children tend to prefer structured and goal-oriented play objects, while extraverted children are more likely to engage with dynamic, sound-producing toys (Daniels, 2011). These insights provide a pathway toward user-centered design that supports emotional durability, defined as the tendency of products to foster enduring affective relationships over time (Chapman, 2015; Mugge, 2018), a key yet often overlooked pillar of sustainable product development. While not yet widely adopted in commercial toy design, temperament-informed frameworks such as ICID offer promising guidance for aligning behavioral profiles with specific play patterns, especially in early prototyping or educational tool development.

2.3 Feature-based toy classification: toward behaviorally aligned design systems

The current market segmentation of toys, often based on age ranges, gender stereotypes, or broad categories like “educational” or “creative”, fails to account for how specific design features shape children’s experiences (Healey et al., 2019; Piaget, 1951). Increasingly, research calls for a shift toward feature-level classification, where attributes such as symmetry, modularity, texture, interactivity, and symbolic potential are treated as primary design variables (Covarrubias Cruz et al., 2022; Wang, 2020).

A prior study identified 15 conceptual clusters of toy design features (Figure 1), spanning cognitive, emotional, sensory, structural, and symbolic dimensions, as a framework for analyzing behavioral alignment in play (Halli and Kaya, under review²). This taxonomy allows for a more granular mapping between

³ The ICID scale is theoretically grounded in the Five-Factor Model (FFM). While it does not use the exact same wording as adult OCEAN measures, its factor structure corresponds directly to the Big Five: Extraversion, Agreeableness, Conscientiousness, Openness, and Emotional Stability (the inverse of Neuroticism). In some studies, this last dimension is referred to as Neuroticism, depending on the phrasing of the items.

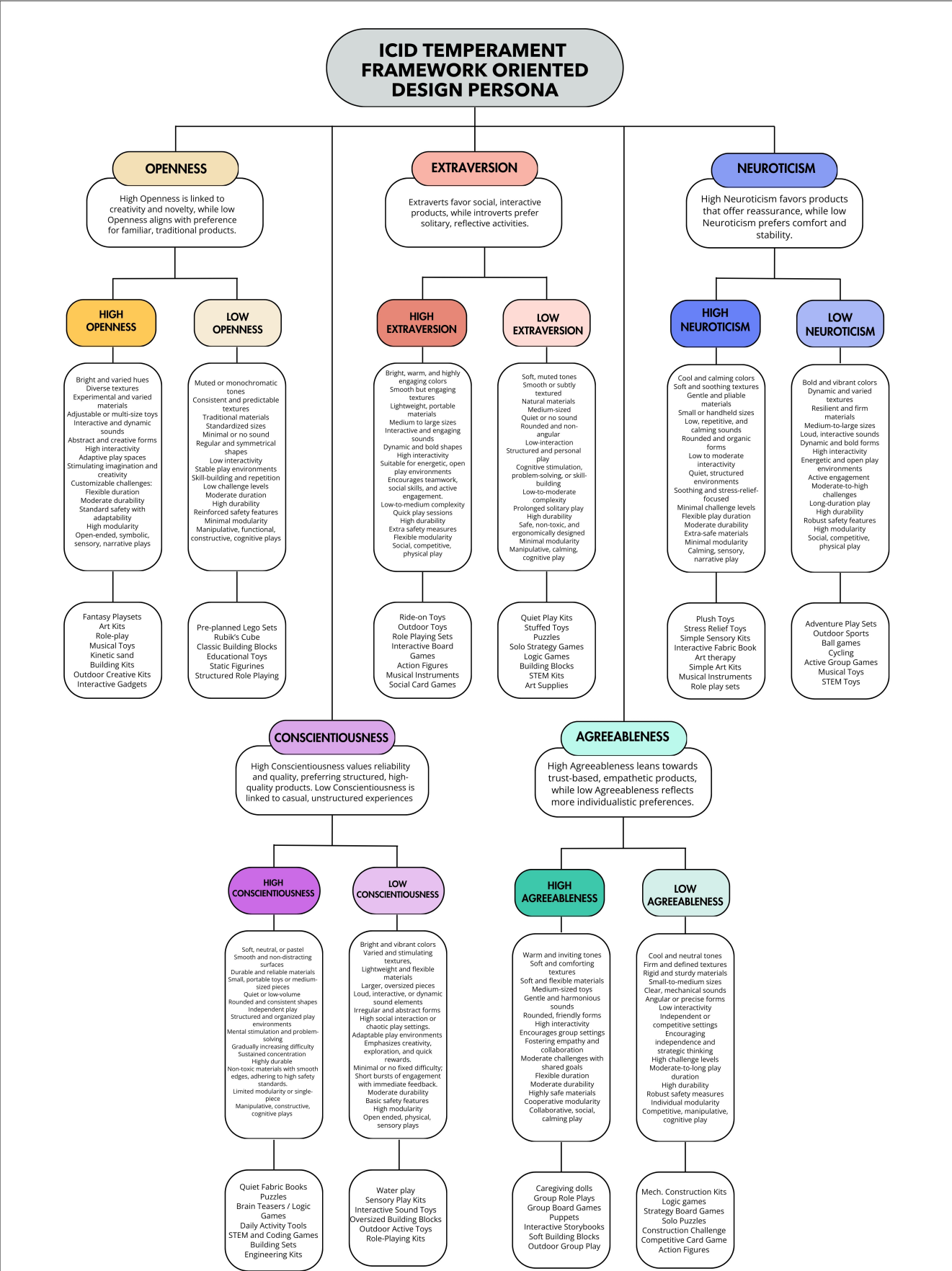


FIGURE 1
The ToyMatch design taxonomy used to classify toy features based on behavioral and sensory dimensions (adopted from Halli and Kaya, under review²).

design characteristics, such as visual appeal, tactile input, modularity, interactivity, and narrative potential, and user behavior. Such specificity enables adaptive, temperament-informed recommendation systems to emerge. Importantly, these features are not neutral: they carry affective, social, and developmental consequences (Hammond, 2014; Richards et al., 2022). For example, toys with open-ended modular structures support creativity and long-term engagement, while overly simplified or stimulus-poor toys may lead to disengagement and abandonment (Alves et al., 2023; Barrick et al., 2005; Hassinger-Das et al., 2021). In this sense, design features act as mediators of emotional durability and cognitive challenge, factors central to both individual development and societal sustainability. By operationalizing toy design as a site of behavioral influence and identity formation, this literature reframing positions toy features not merely as functional elements but as transformative touchpoints in cultivating mindful consumption habits, particularly in the foundational years of life.

2.4 Critical perspectives on recommendation models for children

Existing toy recommendation systems lag behind the more mature ecosystems in film, music, and gaming, where large-scale behavioral datasets enable continuous preference learning and fine-grained personalization (Bi et al., 2024; Li et al., 2017). By contrast, children's toy tools are typically constrained to broad factors, age bands, safety compliance, and developmental milestones, yielding static rather than adaptive personalization (Abdollahpouri and Burke, 2019; El Harrouchi et al., 2025). While necessary, these factors do not explain why some products sustain engagement whereas others are quickly abandoned, an omission that is consequential for sustainability, given rising toy waste driven less by material failure than by lack of emotional or developmental fit (Burns and Gottschalk, 2020).

A core technical challenge is that children's toys generate few digital traces, limiting the effectiveness of collaborative filtering and other data-hungry machine-learning approaches that excel in media platforms (Anantrasirichai and Bull, 2022; Zangerle and Bauer, 2023). Trait-based or personality-inference models imported from adjacent domains face additional hurdles: for children they are ethically sensitive to collect, often coarse-grained, and only weakly predictive of actual play patterns and sustained engagement (Burns and Gottschalk, 2020; Zangerle and Bauer, 2023). In practice, these constraints lead to generic or mismatched toy suggestions that do little to support product longevity or reduce premature disposal.

Beyond data scarcity, existing children's product recommenders rarely integrate three necessary layers: (i) validated temperament structures, (ii) specific toy design attributes shaping play experience, and (iii) caregiver-defined sustainability priorities (Burns and Gottschalk, 2020; Halli et al., 2023; Zangerle and Bauer, 2023). Demographic heuristics (age/gender) further risk stereotype reinforcement, while black-box AI can compromise interpretability and accountability, both critical in childhood contexts where trust,

explainability, and value alignment matter (Bi et al., 2024; El Harrouchi et al., 2025; Li et al., 2017).

Taken together, the literature indicates that next-generation toy recommendation frameworks should:

- Move beyond static age brackets and aggregate trait scores.
- Link validated child temperament/play styles with fine-grained toy features that shape engagement (Halli and Kaya, under review)².
- Incorporate caregiver sustainability values (e.g., longevity, reusability, educationality) in ranking and selection (Halli et al., 2023).
- Operate under data sparsity using ethically appropriate signals (observations, brief surveys, indirect evidence) rather than reliance on large digital traces (Anantrasirichai and Bull, 2022; Zangerle and Bauer, 2023).
- Support circularity by recommending toys likely to engage children serially (re-use, exchange) and to sustain attachment over time (Burns and Gottschalk, 2020).

This is precisely the gap addressed by ToyMatch: it couples empirically derived temperament personas with a detailed taxonomy of toy design attributes, then overlays caregiver sustainability weighting (AHP) to produce low-input, explainable recommendations suited to sparse, child-safe contexts (Bi et al., 2024; Halli et al., under review²; Halli et al., 2023; Li et al., 2017). In doing so, it moves beyond static demographic or trait-first models toward a behaviorally grounded, sustainability-aware framework that is compatible with circular economy objectives. Unlike prior systems that remain descriptive or narrowly predictive, ToyMatch explicitly integrates critique of these limitations by operationalizing a multi-layered, value-aligned framework.

3 Methodology

This study employs a multi-layered, survey-based quantitative design to operationalize the ToyMatch framework. Rather than framing toy selection as a transactional act, it is approached here as a value-alignment process, where children's temperaments and caregivers' sustainability priorities co-shape more emotionally resonant and circular consumption patterns.

3.1 Survey design and participants

This study draws on data collected from 214 caregivers of children, primarily aged 3 to 6, residing in Türkiye. The aim was to empirically evaluate the proposed multi-layered toy recommendation framework by integrating temperament traits, feature-based design responses, and sustainability-aligned prioritizations.

The data were collected through an online survey hosted on Google Forms, with an average completion time of 8–10 min. Participants were recruited via snowball sampling through a combination of researcher networks, parenting-focused WhatsApp groups, targeted Instagram advertisements, and early childhood social media communities. Recruitment efforts were tailored

to reach a diverse pool of Turkish caregivers involved in daily toy selection and use. Ethical approval was granted by Istanbul Technical University (Protocol No. 612, 13 January 2025). All participants provided informed consent digitally prior to participation. The survey was anonymous, voluntary, and participants were free to withdraw at any time.

3.2 Survey sections and constructs

The survey was structured around the three core components of the ToyMatch framework, each corresponding to a conceptual layer in the recommendation system: temperament assessment, toy feature profiling, and preference-based classification.

3.2.1 Temperament profiling via ICID-FFM (Layer 1)

Caregivers assessed their child’s behavioral tendencies using a 5-item short-form tool adapted from ICID, informed by prior evidence linking ICID to the FFM in early childhood applications (Gosling et al., 2003; Halli and Kaya, under review¹). The selected items were designed to reflect the five core FFM dimensions, Openness, Conscientiousness, Extraversion, Agreeableness, and Neuroticism, in a minimal yet interpretable format. The five temperament items were adapted from the widely used five-item short-form of the FFM, commonly employed in adult personality research. Each item was reworded and contextualized to reflect observable behaviors in early childhood, ensuring developmental appropriateness while maintaining conceptual fidelity to the original FFM domains. Selection criteria included empirical relevance, linguistic clarity, and alignment with caregiver-observable traits.

Each item was presented as a single trait spectrum (e.g., “enjoys new experiences” vs. “prefers routine”) and rated by caregivers on a 10-point Likert scale. Each item was anchored at both ends to capture behavioral tendencies along a continuum, enabling a simplified approximation of temperament traits in young children. This approach allowed for the efficient generation of individualized temperament profiles, which then served as the basis for clustering children into design-relevant personas. These personas reflect behavioral readiness for particular toy design modalities and provide a foundation for matching with specific toy attributes.

3.2.2 Toy design feature mapping (Layer 2)

In the second section, caregivers were asked to evaluate the design characteristics of the toy their child most frequently and consistently engaged with, typically the one played with for the longest periods of time per session (Halli et al., under review¹). This section aimed to generate a structured mapping between real-world play experiences and the theoretical design features associated with different temperament traits, drawing on frameworks developed during earlier phases of the project (Halli and Kaya, under review)².

TABLE 1 Summary mapping of FFM traits to key design features and example toy categories.

FFM trait	Key design features	Example toy category
Openness	Bright, experimental, interactive, abstract	Fantasy Playsets
Conscientiousness	Soft, smooth, durable, small, quiet, safe	Puzzle Games
Extraversion	Warm, smooth, light, interactive, competitive	Physical and social games
Agreeableness	Warm, soft, flexible, interactive, collaborative	Board games
Neuroticism	Cool, soft, gentle, small, rounded, sensory	Kinetic sand/play dough

To this end, participants completed a 76-item binary-coded checklist reflecting 15 primary design categories. These categories encompassed a wide range of toy attributes including:

- Visual and structural qualities (e.g., symmetry, vibrant or muted colors, surface detailing)
- Material and sensory properties (e.g., tactile complexity, texture, weight)
- Auditory and interactive aspects (e.g., presence or absence of sound, modular components, mobility)
- Functional, symbolic, and narrative affordances (e.g., use in imaginative play, problem-solving, role-play, or social contexts)

The 76 toy design features were systematically mapped to the five FFM personality traits through a structured procedure (Figure 1). This process built on an initial conceptual framework developed in a separate study (Halli and Kaya, under review)², which synthesized empirical evidence on temperament-linked play preferences (e.g., sensory sensitivity, complexity of play, social engagement) from child development and psychology literature (e.g., Chess and Thomas, 1987; Rothbart, 2019; Rothbart et al., 2001). For features without direct empirical counterparts, theoretical deduction was applied by extrapolating from the polar ends of each FFM dimension, complemented by analogous findings in related domains such as user experience design and environmental psychology. The preliminary mapping was then reviewed by child development specialists and child psychologists to ensure developmental relevance and conceptual clarity. A summary of this mapping is presented in Table 1, while the full correspondence is illustrated in Figure 1, providing a comprehensive link between psychological tendencies and tangible play affordances and offering an interpretive layer to understand how different temperaments may resonate with specific design elements.

To better contextualize the mapping procedure, supplementary exploratory visuals were included. Supplementary Figure S1 illustrates the distribution of design feature selections across participants, offering a general sense of salience and frequency. Supplementary Figure S2 presents the correlation matrix among

features, confirming their conceptual independence and validating the inclusion of distinct design attributes.

3.2.3 ToyMatch classification task (Layer 3)

The third section offered an applied representation of the theoretical model by translating temperament-based design logic into visual toy examples. Caregivers responded to five image-based questions, each featuring three toy options pre-classified according to design attributes associated with the high, moderate, or low expressions of one FFM trait (e.g., Extraversion). These toys embodied distinct design feature clusters derived from the ToyMatch mapping developed during earlier phases of the project (Figure 1).

As illustrated in Table 2, a sample item for the Extraversion dimension included: a silent train for individual, low-social play (Toy 1); a supermarket role-play station (Toy 2) reflecting moderate social engagement; and a movement-based game (Toy 3) representing high physical and social interaction. Participants were asked to choose the toy their child would most likely prefer or engage with.

While not intended as a formal validation instrument, this task provided an observational cross-check of how well theoretical temperament-design alignments resonated with parental intuition in real-world contexts. Subsequent statistical analyses, reported in the Results section, offered more systematic confirmation that this visual classification task aligned with trait-based predictions, especially in dimensions such as Extraversion and Openness.

4 Results

This section reports the key findings from three analyses: cluster profiles based on toy–temperament patterns, regression models testing alignment effects, and a comparative test of the ToyMatch system versus trait-first approaches.

4.1 Cluster analysis: feature-based typologies and temperament alignment

To uncover naturally emerging behavioral archetypes based on children’s toy interactions, an unsupervised clustering analysis was conducted using the 76 binary-coded toy design features. Two complementary methods, K-Means and Hierarchical Agglomerative Clustering (HAC), were applied to ensure robust pattern detection and structural validation. After iterating cluster counts from $k = 2$ through 7, silhouette scores and elbow plots indicated an optimal solution at $k = 5$ (Supplementary Figure S3). HAC dendrogram inspection supported this configuration by revealing nested relationships between certain feature groups, offering thematic coherence across clusters. The stability of this solution was cross-validated by overlap analyses between hierarchical, KMeans, and hybrid methods (Supplementary Figures S4, S5).

Importantly, temperament scores were intentionally excluded from this process to allow design-based groupings to emerge in a purely data-driven manner, without being biased by psychological

TABLE 2 Sample ToyMatch classification task (Extraversion).

Toys	Description	Properties
Toy 1	A compact, modular train set with magnetic connectors	Silent, individual, focused
Toy 2	An interactive supermarket playset including a checkout counter, play groceries, and interactive accessories	Social and interactive
Toy 3	A floor-based movement game combining physical activity with playful animal-themed actions	Physical interaction and social bonding

A visual question showing three toy options associated with low, moderate, and high expressions of Extraversion. Used as part of the behavioral profiling task to infer temperament preferences through.

assumptions. Subsequent analyses linked these five clusters to distinct combinations of design features, such as:

- **Cluster 1 (The Planner):** Structured, rule-based toys emphasizing symmetry, repetition, and cognitive scaffolding;
- **Cluster 2 (The Explorer):** Modular, multi-sensory toys supporting symbolic exploration and creative reconfiguration;
- **Cluster 3 (The Nurturer):** Soft, quiet, emotionally expressive toys aligned with narrative comfort and affective attachment;
- **Cluster 4 (The Performer):** Sound-producing, feedback-driven toys promoting social interaction and dynamic engagement;
- **Cluster 5 (The Dreamer):** Abstract, lightweight, low-structure toys encouraging open-ended, non-linear play patterns.

These clusters were later cross-referenced with FFM temperament scores to evaluate correspondence. Strong alignment emerged for:

- **Conscientiousness** → The Planner (goal-directed, rule-bound features),
- **Extraversion** → The Performer (dynamic, interactive, and sound-based toys),
- **Openness** → The Explorer and The Dreamer (symbolic, reconfigurable, or imaginative designs).

In contrast, Agreeableness and Neuroticism showed more diffuse and inconsistent mappings, potentially due to subjective parental interpretations or less tangible material expressions of these traits. These personas not only reflect statistically emergent patterns but also offer archetypal lenses through which designers and caregivers can intuitively interpret and engage with children’s play preferences.

Demographic trends also emerged: boys were more frequently represented in clusters involving mechanical, sound-based, and competitive toys, while girls were more common in emotionally expressive and symbolic clusters. Additionally, older children (5–6) gravitated toward structured and cognitively engaging toys, whereas younger ones (3–4) showed preferences for tactile and narrative-based designs (Table 3).

These findings reinforce the idea that clustering based on design features alone can reveal latent behavioral patterns that correspond

TABLE 3 Latent personas.

Persona name	Dominant features	Temperament alignment	Demographic trends
The Planner	Symmetry, rule-based, repetition	Conscientiousness	Older boys
The Explorer	Modular, symbolic, sensory	Openness	Mixed
The Nurturer	Soft, emotional, narrative	Neuroticism/Agreeableness	Younger girls
The Performer	Sound, movement, interactive	Extraversion	Boys
The Dreamer	Abstract, open-ended, minimal	Openness	Mixed

meaningfully to psychological tendencies. The distribution of selected features shows clear trends in caregiver preferences (see [Supplementary Figure S1](#)). This suggests that temperament-aligned design strategies need not rely on demographic stereotypes such as age or gender. For instance, traits like Openness were observed across both genders and various age groups, challenging the assumption that certain design inclinations are bound to specific demographic profiles. Such typologies provide a foundational layer for supporting emotional durability, inclusive engagement, and circular play practices.

4.2 Regression analysis: predictive strength of ToyMatch classification

To further validate the temperament-toy alignment, a series of logistic regression models were built to predict each of the five FFM traits from ToyMatch class selections. Multinomial logistic regression was used where applicable, supported by binary models for more polarized groups. SHAP (SHapley Additive exPlanations) value analysis was employed to interpret model outputs and feature contributions ([Supplementary Figures S2, S7–S11](#)). Key findings included:

- Extraversion and Openness yielded the highest predictive performance, with ROC AUC scores above 0.65 in several model runs.
- Conscientiousness showed moderate predictive capacity, often requiring modularity and sensory features to differentiate effectively.
- Agreeableness and Neuroticism showed weaker model fit, potentially due to broader variance in parental interpretation and contextual ambiguity in their toy expressions.

These regression outputs confirmed that a temperament-based recommendation model, especially when grounded in Openness, Extraversion, and Conscientiousness, can reliably inform toy alignment decisions. Notably, in Extraversion prediction (see [Figure 2](#)), SHAP analysis highlighted sound-based and mobile features as key predictors.

Several additional modeling strategies were explored to test reverse pathways, namely, predicting toy feature patterns from FFM trait scores (i.e., Trait → Feature) using multinomial logistic regression and dimension-reduced inputs via PCA. However, these approaches yielded inconsistent or non-interpretable outputs

across most traits, especially for Agreeableness and Neuroticism. As shown in [Supplementary Figure S6](#), the explained variance across PCA components was minimal, further confirming the fragmented and multidimensional nature of the feature space and the limited utility of PCA-based dimensionality reduction. This further validated the decision to prioritize the ToyMatch → Trait direction, which offered stronger predictive performance and clearer interpretability within behaviorally grounded design logic.

4.3 Comparative pathway testing: ToyMatch vs. trait-first approaches

In addition to direct regression analyses, comparative modeling was conducted to evaluate whether trait-to-feature (FFM → Design) or feature-to-trait (ToyMatch → FFM) pathways yielded stronger alignment. While predicting toy features directly from abstract trait (FFM) scores produced unstable results, using ToyMatch classifications as a proxy, rooted in observable play preferences, enabled more consistent and interpretable mappings ([Supplementary Figure S11](#)).

This asymmetry highlights the advantage of behavior-first approaches: rather than asking users to self-report abstract psychological traits, ToyMatch captures their play-based logic, enabling a more grounded and actionable pathway for aligning design features with temperament tendencies.

5 Discussion

This section discusses the implications of the findings across four themes: the comparative success of ToyMatch over trait-based models, the role of interpretive infrastructure in behavioral alignment, practical insights from app-level implementation, directions for future work and key limitations of the study.

5.1 Why ToyMatch performed better than trait-based models

While both trait-based and behavior-based approaches were explored in this study, the ToyMatch system consistently outperformed traditional trait-to-feature models across multiple

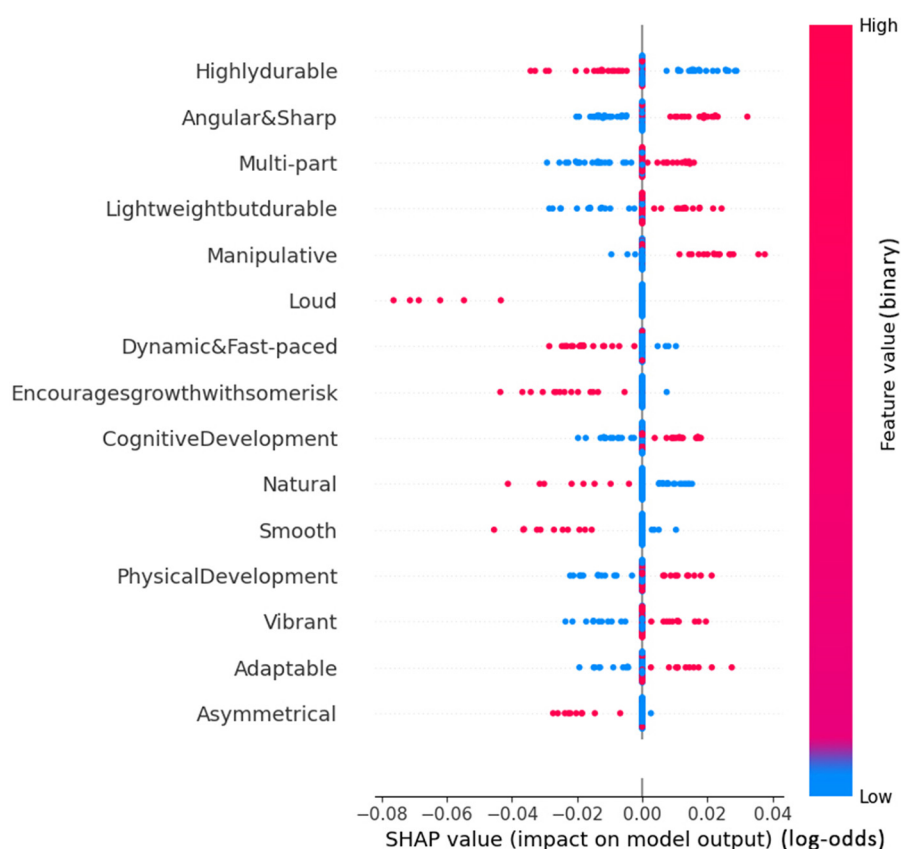


FIGURE 2

SHAP summary plot for predicting high Extraversion (class = 1). Key influencing features include loudness, dynamic movement, modularity, and manipulability.

evaluation criteria. Attempts to predict design preferences directly from FFM trait scores yielded weak or inconsistent results (Table 4). For instance, regression models using raw FFM scores as predictors generated low ROC AUC values, particularly for traits like Agreeableness (ROC AUC = 0.54) and Neuroticism (ROC AUC = 0.50), indicating limited predictive utility. Even dimensionality-reduced inputs via PCA offered little improvement, reinforcing the limited explanatory power of trait-first models.

By contrast, the reverse pathway, predicting temperament traits from ToyMatch-derived design clusters, proved far more robust. ToyMatch → Trait predictions, supported by logistic regression and SHAP-based feature interpretation, yielded notably higher performance for Extraversion (ROC AUC = 0.74, F1 = 0.68, Accuracy = 0.79), Conscientiousness (ROC AUC = 0.58, F1 = 0.67, Accuracy = 0.67; despite a marginal drop in AUC compared to trait-first models, F1 and Accuracy showed meaningful improvements), and Openness (ROC AUC = 0.67, F1 = 0.43, Accuracy = 0.75), revealing consistent and interpretable alignment between clustered design behaviors and psychological tendencies. These results empirically demonstrate that the ToyMatch axis provides more reliable prediction than raw traits: for instance, the Extraversion gain confirms that dynamic, socially oriented play behaviors are more accurately captured through clustered design features,

while the Openness result shows how exploratory toy features align with imaginative tendencies. Conscientiousness further illustrates how structured play signals (e.g., long/focused engagement) translate into more reliable classification than abstract trait ratings.

This contrast makes the asymmetry unmistakable: whereas Trait → Feature prediction was almost entirely unsuccessful, ToyMatch → Trait classification demonstrated clear and practically useful gains, particularly for Extraversion, and for Conscientiousness where F1 and Accuracy improved more than 100% despite the slight ROC AUC decrease. In other words, ToyMatch is not only conceptually stronger but also empirically effective in real-world classification tasks. One reason ToyMatch outperforms trait-first models may lie in the nature of behavioral data itself. Whereas trait scores, often based on self- or proxy-reported measures, are abstract and susceptible to bias, observed or inferred behavioral choices (such as toy selection patterns) offer more tangible, contextualized indicators of a child's interaction style. This grounded approach likely enables more precise and reliable alignment with design features, especially in early childhood where personality is still fluid and emergent.

This empirical edge also distinguishes ToyMatch from other recommendation approaches. Demographic filtering (age/gender heuristics) ignores behavioral nuance and risks reinforcing

TABLE 4 Comparison of ROC AUC scores for Trait/Feature/ToyMatch scores.

Prediction pathway	Trait	ROC AUC	F1 score	Accuracy
Trait → Feature	Extraversion	0.62	0.32	0.45
Trait → Feature	Conscientiousness	0.59	0.32	0.32
Trait → Feature	Openness	0.56	0.33	0.32
ToyMatch → Trait	Extraversion	0.77	0.68	0.79
ToyMatch → Trait	Conscientiousness	0.58	0.67	0.67
ToyMatch → Trait	Openness	0.67	0.43	0.75

Bold values mark the superior results obtained when predicting traits from ToyMatch scores, compared with predictions from raw trait-to-feature models. These highlight that ToyMatch-based pathways yield higher ROC AUC, F1, and Accuracy values for Extraversion, Conscientiousness, and Openness, demonstrating the relative predictive advantage of the ToyMatch framework.

stereotypes; collaborative filtering requires large datasets and often struggles with novelty; and black-box AI systems may provide accuracy but lack interpretability. By contrast, ToyMatch balances predictive performance with transparency, offering a behaviorally grounded, explainable pathway that caregivers and designers can trust.

This asymmetry highlights a core insight: behaviorally grounded systems may offer more reliable and actionable mappings than abstract self- or proxy-reported trait data. In particular, when working with young children whose personalities are still forming and whose traits are interpreted through caregivers, traditional personality inventories may introduce bias or ambiguity (Supplementary Figure S12). Caregivers may, for example, systematically overreport positive traits such as Extraversion and Conscientiousness, while underreporting traits like Neuroticism, partly due to social desirability bias or aspirational perceptions of their child. This tendency stands in contrast to developmental research indicating that preschool-aged children typically exhibit lower levels of self-regulation and sociability, and higher levels of emotional reactivity (Morales-Vives et al., 2017; Zupančič, 2008).

These findings not only underscore a methodological advantage but also reflect a deeper shift in mindset: from assessing static personality labels to observing dynamic, context-sensitive behavioral cues. By anchoring prediction in observed or inferred play behavior, rather than abstract trait labels, ToyMatch provides a more ecologically valid and ethically defensible foundation for recommendation (Supplementary Figure S13). The system's logic rests not on judging a child's personality, but on interpreting the behavioral implications of toy engagement. This positions ToyMatch as a more predictive, inclusive, and culturally adaptable model, better suited to supporting long-term emotional durability and sustainable consumption decisions.

5.2 Interpretive infrastructure: a behavioral bridge for design

While recommendation systems are often framed as technical engines, ToyMatch functions instead as an interpretive infrastructure, one that translates complex behavioral dispositions into actionable design decisions. It is not merely a classification

tool, but a meaning-making interface that maps inner traits onto material attributes in a way that supports ethical, sustainable, and developmentally aligned consumption. In this context, personalization is not about reinforcing preference but about amplifying potential, to grow, adapt, imagine, and care.

The empirical findings demonstrated that the 76 binary-coded design features, when analyzed in isolation, were insufficient to reliably predict psychological traits. Attempts to regress toy features directly from FFM scores produced inconsistent or uninterpretable outputs, especially for traits like Agreeableness and Neuroticism. For example, the markedly higher ROC AUC observed for Extraversion (0.77 vs. 0.62 in trait-first models) shows concretely how ToyMatch captures socially oriented play signals more effectively than raw trait inputs. Similarly, the Openness axis (0.67 vs. 0.56) illustrates how exploratory design features provide a stronger empirical anchor for imaginative tendencies than abstract trait ratings. These results ground the conceptual bridge directly in measurable performance gains. ToyMatch offers a mid-layer structure between human-centered behavioral insight and machine-executable logic. By aggregating temperament tendencies into clustered personas and linking these personas to pre-defined design patterns, it transforms data into design-relevant meaning. In this way, ToyMatch mimics the interpretive role of a designer or caregiver, translating subtle behaviors into informed decisions, yet does so systematically and without cultural or emotional bias.

This stands in contrast to alternative recommendation approaches. Demographic heuristics (age/gender filtering) are simple but risk stereotyping; collaborative filtering requires large-scale data and fails with novel or niche toys; and black-box AI models may offer accuracy but lack interpretability, which is critical in childhood contexts. ToyMatch, by comparison, balances predictive robustness with transparency, enabling both caregivers and designers to understand why a recommendation is made. This infrastructure also challenges the dominant assumption that more granular data alone leads to better predictions. Instead, it demonstrates that curated behavioral abstractions, like those operationalized through ToyMatch, offer more consistent and ethically aligned outputs. The system reflects a hybrid logic: one that leverages machine intelligence for pattern detection while preserving human-level interpretability in its recommendation rationale. This balance is especially crucial in childhood contexts, where design decisions must account not only for accuracy but also for care, trust, and imagination.

5.3 App-level implementation and practical pathways

Building on the empirical findings and behavioral advantages of the ToyMatch framework, we propose a low-input, high-interpretability recommendation flow designed for real-world application. The core logic of the system prioritizes usability, interpretability, and behavioral fidelity, balancing minimal caregiver effort with maximum contextual intelligence.

At the input level (Figure 3), the system only requires a child's age and gender (optional), five toy choices from pre-classified sets aligned with the FFM framework, and, if indicated by the initial selections, a brief (5 questions) follow-up temperament questionnaire. This enables caregivers to engage with the system quickly, without the need for lengthy psychometric tests or demographic profiling. Figure 4 outlines this logic in an accessible visual format:

- Based on the initial toy choices made by caregivers (on behalf of the child), the system computes ToyMatch scores for each FFM trait.
- If the child's toy preferences indicate 2–3 clear trait extremes, the system recommends toys aligned to these dominant traits.
- If only one trait extreme is matched, recommendations are made along the main personality axis.
- If 4–5 extremes are matched, suggesting complex or conflicting signals, a short follow-up questionnaire based on the ICID is triggered to refine the temperament profile.
- In all cases, the system recommends three suitable toys mapped from predefined design-persona profiles.
- Caregivers are then asked which toy they would most likely choose, or whether none seem appropriate. These responses create a feedback loop that helps improve the system's predictive model over time.

This application structure embodies a regenerative mindset in several ways. First, it resists static segmentation based on age or gender, avoiding the common pitfalls of stereotype-based recommendation engines. While some demographic patterns (e.g., older boys preferring mechanical or sound-based toys) were observed during analysis, these were treated as descriptive, not prescriptive. ToyMatch refrains from using such trends to guide its suggestions, instead anchoring its logic in behaviorally grounded, inclusive matching.

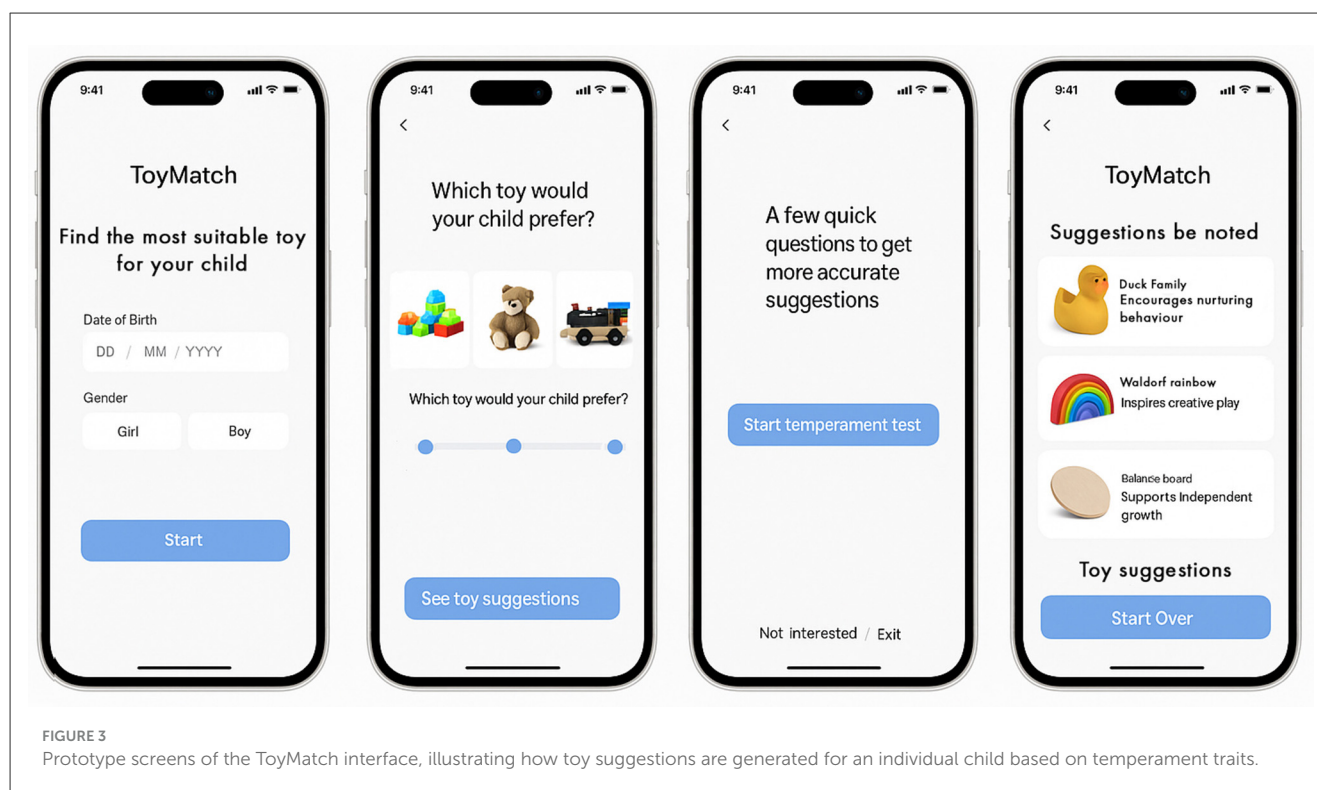
In parallel with temperament-persona alignment, the system also incorporates a second evaluation layer based on caregiver sustainability priorities. Drawing from AHP scores collected in earlier stages, each toy in the database is assigned a sustainability-informed value, balancing factors such as educational value, entertainment, and adaptability over time (Halli et al., 2023). These scores are not shown to the user but are integrated as weighted modifiers during final recommendation ranking. As a result, even among toys that match a child's temperament, those that better align with the caregiver's values are given higher priority. This dual-layer structure ensures that ToyMatch supports not only behavioral resonance but also long-term emotional durability and sustainable consumption.

Table 5 illustrates the toy suggestion for the class code O+ (Maximum Openness), which includes features such as imaginative play, experimental materials, and symbolic expression, the system evaluates matching toy categories and scores them across multiple criteria, including age fit, educational challenge, and sustainability values as defined by caregivers. In this case, "Fantasy Playsets" emerges as the top recommendation with a 13.7 compatibility score, aligning with both the child's temperament and the caregiver's sustainability priorities. While the decision-making logic is built on a transparent and interpretable scoring architecture, as illustrated through internal scoring tables in this study, the user-facing mobile interface remains minimal, intuitive, and interactive. This ensures that ethical and data-driven personalization occurs behind the scenes, while offering stereotype-free suggestions to caregivers. By doing so, the end-to-end system transforms abstract psychological profiling into a concrete, participatory, and ethically aligned design flow.

Beyond its immediate functionality, however, the ToyMatch framework holds the potential to cultivate deeper shifts in caregiver thinking. Grounded in behaviorally interpretable interactions, the system may serve as a subtle but repeated cueing mechanism for reflective decision-making and value alignment. This orientation aligns with theoretical perspectives such as Mezirow's Transformative Learning Theory, which emphasizes how new frames of reference emerge through critical reflection (Mezirow, 2018; VanWynsberghe, 2022); Kegan's Constructive-Developmental Theory, which addresses shifts in meaning-making complexity (Girgis et al., 2018; Kegan, 1998); and Sterling's notion of "sustainability mindsets" as long-term capacities for systemic thinking and ethical awareness (Sterling, 2010, 2024). While these frameworks were not empirically tested here, they offer a promising lens for future longitudinal studies investigating whether tools like ToyMatch can catalyze deeper attitudinal shifts toward more sustainable and developmentally attuned consumption.

The app encourages long-term use and emotional connection, which in turn supports circular consumption behaviors. By aligning toys with children's psychological dispositions rather than transient market categories, it fosters deeper, more sustainable engagement, reducing the likelihood of early abandonment or mismatched purchases. Finally, the system's "low barrier, high intelligence" model reflects an ethical design philosophy: to make personalization more accessible without requiring excessive data collection, while still upholding values of care, adaptability, and social neutrality. In doing so, ToyMatch bridges the gap between technological personalization and the behavioral foundations of circular society goals, offering not just a product interface but a participatory infrastructure for emotionally durable and mindful consumption. While early childhood is often framed as a passive stage of consumption, this system reframes toy selection as an active site of meaning-making and value negotiation, mediated by caregivers but grounded in children's emerging dispositions.

At the same time, it is important to acknowledge that the development of a digital application entails its own resource and energy costs. ToyMatch addresses this by being conceived within a systems-thinking approach to circularity. By optimizing toy-child alignment, the system seeks to extend



product lifespans, reduce premature disposal, and minimize overproduction, thereby offsetting some of the environmental footprint associated with its digital infrastructure. Its lightweight architecture enables integration into existing caregiver or retailer platforms without significant additional computational demands. In practice, caregivers can use ToyMatch, either online or offline, during shopping to make more informed choices, while retailers can embed the tool to support sales of well-matched products. Designers and manufacturers may further employ the framework to create new products that align with identified personas, enhancing emotional durability, functional longevity, and resource efficiency. Potential production benefits include optimized material use, prevention of overstock-related waste, and support for demand-responsive manufacturing. Future iterations could also incorporate explicit sustainability metrics for the tool itself, ensuring that its delivery mechanism reflects the same circular principles it promotes. Compared to collaborative filtering or content-based approaches widely used in digital media recommendation (Bi et al., 2024; Li et al., 2017), ToyMatch's advantage lies in its ability to operate without large-scale digital traces, an essential condition in childhood contexts. While such models remain effective for film, music, or gaming, they risk producing generic or ethically problematic outcomes in toy contexts. Our findings highlight that behaviorally grounded, sustainability-aware frameworks like ToyMatch may be better suited for domains where data is sparse and value alignment is critical. In addition, a dedicated manufacturer-facing interface could enable more targeted product development, facilitate entry into niche markets, and strengthen brand differentiation through sustainable, high-value customization.

5.4 Future work

The ToyMatch framework opens several promising directions for future research and development, both as a scientific model and as a practical tool for advancing sustainable and emotionally intelligent childhood consumption. First, longitudinal follow-up studies are needed to empirically assess whether temperament-aligned toy recommendations lead to longer-term use, deeper emotional attachment, or reduced rates of premature disposal. While this study infers emotional durability based on design-trait alignment, direct observation of play patterns over time would provide stronger evidence for ToyMatch's impact on circular behavior loops.

Second, cross-cultural validation is essential for testing the generalizability of the current findings. Cultural norms around parenting, gender expectations, and developmental values can significantly shape toy preferences. Implementing the ToyMatch system in diverse socio-cultural contexts would offer valuable comparative insights and allow for localized adjustments that respect contextual nuances while maintaining the system's core behavioral logic. Future studies could specifically investigate how parenting norms and value systems shape toy preferences in different cultural settings, for instance, how collectivist vs. individualist values might influence the prioritization of features such as modularity, symbolic play potential, or adaptability. Third, future iterations of the ToyMatch platform may benefit from AI-based training mechanisms, enabling the system to refine recommendations based on user interaction data over time. Such learning loops, built from toy selection behavior, feedback scores, and engagement duration, could evolve the system into a semi-autonomous tool that dynamically adapts to emerging

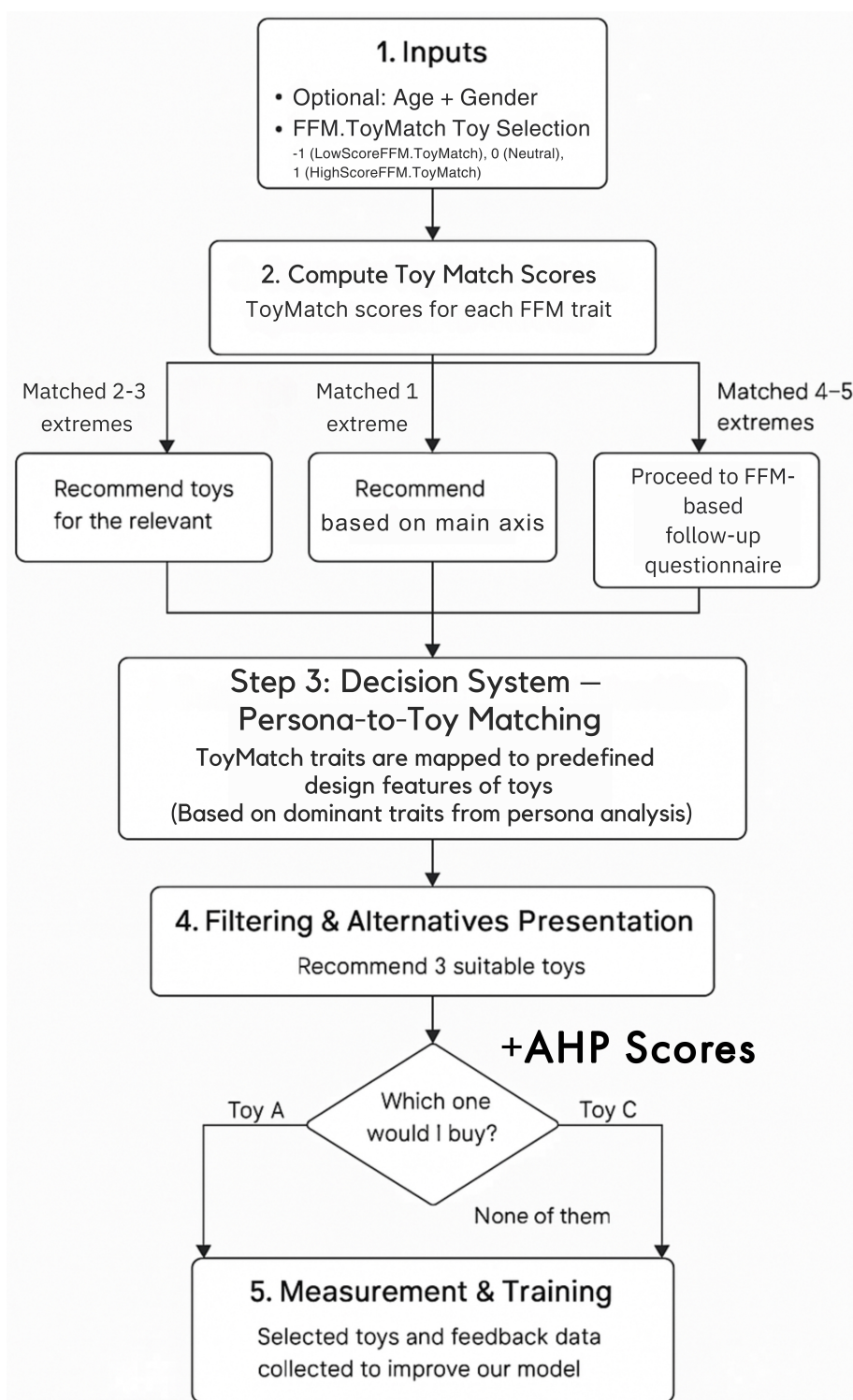


FIGURE 4

The ToyMatch recommendation flow, a low-input, feedback-informed system built on behavioral alignment and stereotype-neutral design logic.

patterns in child development and design preferences, while remaining transparent and ethically interpretable. These learning loops will not only refine the system technically but also advance a deeper strategic role for AI, moving beyond personalization toward shaping circular behavior loops. In this framing, machine

intelligence becomes not merely an optimization tool, but a cultural actor in enabling mindful, sustainable development from early childhood onward. As recent scholarship highlights, AI-based recommendation systems, particularly when deployed in high-engagement, media-rich platforms like YouTube, can actively

TABLE 5 An example of how ToyMatch generates toy suggestions for a child with high Openness traits.

Class_code		Description							Suggested_Toys			
O+		Bright and varied hues Diverse textures Experimental and varied materials Adjustable or multi-size toys Interactive and dynamic sounds High interactivity Adaptive play spaces Stimulating imagination and creativity Customizable challenges: Flexible duration Moderate durability Standard safety with adaptability High modularity Open-ended, symbolic, sensory, narrative plays							Fantasy Playsets Art Kits Role-play Musical Toys Kinetic sand Building Kits Outdoor Creative Kits Interactive Gadgets			
Toy_1	Toy. Match. Score	Product	Gender	Age	Educational _Challenging	Durability	Fun. Factor	Looks. Nice	Price	Recommendation	Second. hand_Market	Updating
Fantasy Playsets	13.7 / 15	A soft, circular play mat featuring bright colors and a zoo scene, paired with detachable figures including animals, a train, and caretakers	Unisex	3+	4	4.1	4.6	4.8	1150		4.3	4

ToyMatch scores represent the degree of alignment between a child's temperament trait (here, high Openness) and toy design features, based on a predefined set of 15 feature descriptors. Suggested toy categories illustrate examples with the highest potential match. The detailed toy example (Fantasy Playsets) shows how the ToyMatch score is combined with age, gender, and Analytic Hierarchy Process (AHP)-based sustainability criteria (e.g., durability, fun factor, aesthetics, price) to generate a final recommendation (follows the approach established in [Halli et al., 2023](#)).

shape user awareness and promote new forms of circular behavior (Tsironis et al., 2024b). In alignment with such architectures, ToyMatch holds the potential to evolve into a culturally responsive system that not only learns but teaches sustainable patterns.

The ToyMatch system, in the future, may also benefit from more nuanced modeling of design–trait relationships. While current mappings rely on binary-coded feature expressions, not all traits exhibit symmetrical preferences. For example, children high in Extraversion may actively seek out sound-producing toys, whereas those low in Extraversion (i.e., introverted) may not necessarily prefer entirely silent toys, but rather a different type of sensory input (e.g., tactile or textural stimulation). This asymmetry suggests that some design preferences may emerge not from direct oppositions but from complementary or compensatory needs, pointing toward a more gradient-based or relational approach to trait–feature matching.

Finally, open-source versions of the ToyMatch engine could be developed, offering modular access for educators, designers, or researchers. This might take the form of an API for educational game developers, a plug-in for learning platforms, or an interactive design tool that supports empathy-based product development. By making its behavioral logic accessible across domains, ToyMatch has the potential to inform not only consumption decisions but also design pedagogy, early childhood education, and product innovation, serving as a bridge between user-centered design and systemic cultural transformation. Such trans-sectoral accessibility aligns with emerging insights from circular economy research that emphasize the growing prevalence of reuse-, reduce-, and redesign-based strategies in corporate platforms (Tsironis et al., 2024a), underscoring the need for emotionally durable design infrastructures even at industrial scale. ToyMatch reclaims personalization not as a tool for reinforcing preferences, but as a means to cultivate emotionally intelligent relationships with objects, aligning individual needs with collective ecological futures. In initial dissemination settings, the ToyMatch model also drew interest from educators working in Montessori-inspired environments, who noted its potential to inform the design of learning materials attuned to children's emotional and developmental profiles. Such feedback points to future collaborative applications, where the system's behavioral mapping could support not only product recommendations but also the co-creation of educational tools that align with pedagogical values like autonomy, empathy, and developmental pacing. This suggests a broader potential for ToyMatch to act as a bridge between sustainable design logic and child-centered learning environments.

Although the current study focuses on leisure-oriented toys, the underlying logic of temperament-aligned design holds potential for expansion into educational and therapeutic contexts. For instance, prior research suggests that children high in Neuroticism may benefit from sensory regulation tools (Purpura et al., 2023), an insight that could guide the selection or design of therapeutic learning materials. Extending ToyMatch into educational toy systems or special needs interventions could offer structured ways to translate psychological insights into pedagogical or developmental strategies, enhancing both emotional wellbeing and learning engagement.

Beyond the current 3–6 age group focus, the underlying architecture of ToyMatch is adaptable to broader childhood stages and adjacent domains of child-centered design. Future adaptations may explore recalibration for older children, educational toolkits, or emotionally durable products in related categories. Far from being a niche application, this system proposes a scalable design infrastructure that can: (i) Be embedded into digital retail and educational platforms, (ii) Inform ethical procurement in schools and public childcare programs, (iii) Shape eco-labeling standards around emotional durability and developmental relevance, (iv) Guide designers in crafting products that grow with the child, rather than expire with age.

Such pathways reflect ToyMatch's foundational commitment: not to prescribe universal solutions, but to co-create adaptive, culturally responsive, and emotionally attuned infrastructures for sustainable childhood futures. These future directions do not only signal technical extensions, but also point to broader systemic potentials. This may offer new pedagogical pathways for embedding sustainability mindsets into early learning environments, beyond curriculum, through emotionally resonant material choices. It may help shift everyday parenting practices toward more reflective, value-aligned consumption, anchoring sustainability in daily micro-decisions rather than abstract ideals. It may also guide designers and manufacturers in creating emotionally durable products that extend beyond age categories, reducing premature obsolescence at scale.

From a game design perspective, ToyMatch also offers a logic for aligning play mechanics with developmental traits, helping manufacturers decide when to emphasize collaborative vs. competitive dynamics, open-ended exploration vs. structured progression, or sensory vs. symbolic play. Unlike digital games where overproduction is not a concern, physical and hybrid toys carry direct material and energy costs, making misalignment riskier. By linking psychological traits with design features, ToyMatch can guide more modular and adaptable game architectures that grow with the child, extending product lifespans while reducing premature obsolescence. In doing so, the framework encourages manufacturers to rethink game design not only as entertainment, but as a lever for emotional durability and circular value.

In terms of practical implementation, ToyMatch may follow different pathways for large-scale and small-scale manufacturers. For high-volume producers, the system offers a means to segment markets based on temperament-aligned personas, enabling agile reconfiguration of production lines to create targeted variants rather than relying solely on mass “one-size-fits-all” models. This targeted diversification can reduce unsold inventory and optimize resource allocation across global distribution networks. For smaller or niche-focused producers, ToyMatch provides a structured way to differentiate products through high-value customization, entering markets that prioritize educational alignment, sustainability, or unique developmental features. By leveraging persona-driven insights, such manufacturers can focus on lower-volume, higher-margin offerings that appeal to discerning caregivers seeking tailored, sustainable products. In both contexts, the framework supports a shift toward more responsive, resource-efficient

manufacturing ecosystems, enhancing competitiveness while reducing environmental impact.

Conceptually, these values differ from a Social Life Cycle Assessment (SLCA) approach, which examines social and ethical impacts across the product's life cycle, such as the use of local materials, fair trade, or fair wage practices. Although such dimensions remain outside the current system's scope, which focuses on aligning existing toys with child developmental profiles, they could be incorporated in future iterations, particularly for manufacturers able to provide verified supply-chain data. Incorporating these criteria may be especially advantageous for small and locally oriented producers, enabling them to leverage regional production strengths, fair-trade networks, and sustainability credentials to differentiate themselves alongside larger industry players.

5.5 Limitations

While the ToyMatch system demonstrates strong potential for advancing behaviorally informed, value-aligned toy recommendations, several limitations must be acknowledged, particularly with respect to interpretation, generalizability, and methodological scope. First, the temperament profiles used in this study rely on caregiver-reported data, which may be subject to social desirability bias. Especially in collectivist cultural contexts such as Türkiye, caregivers may unintentionally overstate positive traits or underreport emotional volatility in their children (Saraç and Koç, 2020). This could help explain the relatively lower predictive accuracy observed in traits like Agreeableness and Neuroticism, where subjective perception and emotional nuance play a greater role in caregiver judgment.

Second, while the ICID-FFM model and design-feature mapping offer robust theoretical grounding, the predictive performance for Agreeableness and Neuroticism traits remained weak across both regression and SHAP-based analyses. This suggests that these traits may require more sensitive or context-specific measurement tools, or may not manifest as reliably in tangible toy preferences compared to traits like Extraversion or Openness. Although the binary-coded taxonomy of 76 features across 15 design categories provided a structured framework, not all theoretically relevant oppositional traits (e.g., noisy vs. silent, rigid vs. flexible) were fully captured in the survey format. This omission was partly due to practical constraints around survey length and caregiver comprehension, as well as the challenge of finding direct linguistic or visual equivalents for certain nuanced design attributes. Third, the empirical sample was drawn exclusively from Turkish caregivers, whose cultural expectations around education, emotional expression, and gender norms may differ significantly from other contexts. While Türkiye provides a rich and relevant site for investigating value-based toy preferences, the findings may not be directly generalizable to other regions without further cross-cultural validation as toy preferences in Türkiye may reflect strong cultural emphasis on educational attainment, emotional moderation, and structured parenting roles.

Additionally, the sustainability priorities used in the recommendation layer were derived from a prior AHP-based

study conducted with a broader caregiver sample (Halli et al., 2023), rather than personalized inputs at the point of use. While this approach avoided burdening users with additional questions (e.g., 28-item pairwise comparisons), it also meant that individual caregiver values may not have been fully reflected in the final toy rankings, potentially overlooking preferences for criteria such as affordability, educational value, playfulness, or long-term adaptability. This limitation underscores the trade-off between usability and precision in preference-sensitive systems and highlights an area for future adaptive interface design, one that could dynamically calibrate sustainability priorities based on minimal user feedback.

Finally, although ToyMatch aims to support emotionally durable and circular toy engagement, the study did not directly measure emotional durability or long-term use behaviors. Instead, these outcomes are inferred based on alignment between child traits and toy design features, supported by caregiver-reported preferences. Future longitudinal or observational studies would be necessary to confirm whether such alignment translates into longer engagement or reduced toy disposal in practice.

These limitations highlight important opportunities for future development, particularly in refining temperament assessment tools, expanding cultural diversity in the dataset, and testing emotional durability through usage-based metrics. They also underscore the importance of ethical interpretation of AI-driven systems: algorithmic outputs should not be treated as fixed truths, but as context-sensitive guides within a broader decision-making ecology. In this regard, the ToyMatch framework must also address specific ethical risks, including over-personalization, premature labeling, and parental dependency on algorithmic guidance. To mitigate these concerns, recommendations are presented as suggestive rather than prescriptive, and always include a diverse set of options that support both existing strengths and potential growth opportunities. This diversity ensures that children are not confined to narrow categories, but are instead encouraged to explore multiple developmental pathways. Rather than deterministic trait-toy mapping, the recommendation logic is grounded in caregiver-prioritized values identified in prior research (Halli et al., 2023), namely educational potential, enjoyment, and adaptability, helping to safeguard flexibility and family agency. While gender information is collected for potential analytical refinement, the system operates in a gender-neutral mode by default, ensuring that outputs do not reinforce stereotypes. Any demographic data are subject to ongoing validation to minimize bias and to protect equitable access across all toy categories.

6 Conclusion

This study introduced ToyMatch, a multi-layered recommendation system that links children's temperament traits with value-informed toy design features to support emotionally durable and ethically aligned consumption in early childhood. By integrating behavioral psychology, design features, and caregivers' sustainability priorities, the system offers a practical alternative to age- or stereotype-based recommendation models. Rather than relying on abstract clusters, ToyMatch adopts interpretable and emotionally resonant persona labels to improve real-world

usability and long-term engagement. These findings suggest that behavior-first systems like ToyMatch not only increase alignment between child needs and product features, but also offer a scalable pathway for cultivating circular thinking from the earliest years of life. As such, the model contributes to broader discussions on sustainability by emphasizing emotional connection and behavioral relevance, expanding the scope of circular design beyond materials to include values, relationships, and developmental resonance.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Ethics statement

The studies involving humans were approved by Istanbul Technical University (Protocol No. 612, 13 January 2025). The studies were conducted in accordance with the local legislation and institutional requirements. The ethics committee/institutional review board waived the requirement of written informed consent for participation from the participants or the participants' legal guardians/next of kin because participation was fully voluntary, anonymous, and conducted through an online survey platform where participants were presented with clear participation terms and explicitly agreed to proceed before starting the survey. No personally identifiable information was collected, and the data collection posed minimal risk.

Author contributions

SH: Conceptualization, Methodology, Investigation, Data curation, Formal analysis, Software, Visualization, Writing – original draft, Writing – review & editing, Project administration. CK: Supervision, Writing – review & editing. BT: Supervision, Validation, Writing – review & editing.

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Conflict of interest

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.

Generative AI statement

The author(s) declare that Gen AI was used in the creation of this manuscript. OpenAI's ChatGPT-4 (2024 version, <https://chat.openai.com>) was used to support the writing process by improving sentence clarity, restructuring certain paragraphs, and ensuring fluency in the narrative. All content was reviewed and finalized by the author, who takes full responsibility for the accuracy and integrity of the manuscript.

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Supplementary material

The Supplementary Material for this article can be found online at: <https://www.frontiersin.org/articles/10.3389/frsus.2025.1668084/full#supplementary-material>

SUPPLEMENTARY FIGURE S1

Bar chart showing the frequency of selected design features across the full sample, highlighting dominant preferences.

SUPPLEMENTARY FIGURE S2

Correlation matrix between individual design features, indicating minimal redundancy ($|r| < 0.7$) across the design variable set.

SUPPLEMENTARY FIGURE S3

Cluster analysis results visualizing participant segments based on design-feature selection.

SUPPLEMENTARY FIGURE S4

Confusion matrix comparing hierarchical and KMeans clustering assignments, illustrating overlap and divergence between segmentation methods.

SUPPLEMENTARY FIGURE S5

Confusion matrix comparing hybrid and hierarchical clustering results, used to test composite persona formation.

SUPPLEMENTARY FIGURE S6

Explained variance ratios across 76 components in PCA analysis, indicating multidimensional structure of toy feature dataset.

SUPPLEMENTARY FIGURE S7

Correlation matrix between FFM traits and ToyMatch scores, revealing strongest alignment in Extraversion and Conscientiousness dimensions.

SUPPLEMENTARY FIGURE S8

Heatmap of dominant trait pairings (exactly two traits), including directional polarity (positive/negative) based on ToyMatch profiling logic.

SUPPLEMENTARY FIGURE S9

XGBoost model results showing feature importance rankings in predicting trait-based toy alignment.

SUPPLEMENTARY FIGURE S10

SHAP summary plot displaying average impact of design features on model output, used to interpret feature-level contributions.

SUPPLEMENTARY FIGURE S11

Boxplot comparing Extraversion trait scores with corresponding ToyMatch classifications, validating behavioral labeling accuracy.

SUPPLEMENTARY FIGURE S12

Distribution of FFM personality scores across the sample ($N = 214$).

SUPPLEMENTARY FIGURE S13

ToyMatch score distributions per trait dimension, showing predictive ($N = 214$) patterns.

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