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The need for a triangle comparison among Chinese characters, Pinyin, and English: from behavioral and neurophysiological perspectives

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The current study reviewed previous research comparing Chinese and English from behavioral and, emphatically, neurophysiological perspectives. We found that previous studies have identified the time course and brain activation locations involved in processing Chinese and English. At the same time, most of them focus on comparing Chinese characters with English or Chinese characters with Hanyu Pinyin, leaving a gap in the comparison between Pinyin and English, which is essential in understanding the relationship between Chinese and English cognition. By summarizing the indices of previous fMRI and EEG studies, we conceived the idea of comparing Hanyu Pinyin and English using a future experimental paradigm. Meanwhile, Pinyin's role in character input and reading development in Chinese children was also an intriguing topic for future research.

KEYWORDS

Chinese, English, Pinyin, comparison, neurophysiological

1 Introduction

Studying the mechanisms of language processing has been a crucial topic for scientists in both linguistic and cognitive science fields. Besides studies in alphabetic languages, research on Chinese recognition and production mechanisms has also been conducted since the 1960s, using methods such as contrast analysis and Error analysis, as well as psycholinguistic and neurophysiological approaches since the 1980s.

However, we should note that the Chinese used in mainland China is also deeply related to Hanyu Pinyin, which attracts less attention. In fact, Pinyin is frequently used in our daily lives and holds a critical position in the lives of Chinese speakers.

Hanyu Pinyin, also known as Pinyin or Chinese Phonetic Alphabet, is an auxiliary system that represents characters, aiming to help native Chinese speakers (both children and adults) and Chinese learners spell the characters. It was invented in the 1950s in mainland China to help the government eliminate illiteracy and to assist native Chinese speakers in learning the pronunciation of new characters.

Pinyin strengthens the relationship between the orthography and phonology of Chinese characters, serving as an essential tool for learners of Chinese to acquire the language (Chen et al., 2016a). Moreover, Pinyin is also used in daily life when people type it into computers and mobile phones. Every student learns Pinyin in elementary school, typically in Grade One or even kindergarten, and comes across it almost daily. Therefore, Pinyin is of great importance to native Chinese speakers. Moreover, several studies have suggested that the learning ability and scores in Pinyin influence the phonological awareness of Chinese children (discussed in Section 1), which in turn leads to the development of both Chinese reading ability and English acquisition effectiveness.

Additionally, when teaching Chinese as a second language, international students worldwide are required to learn Pinyin at the beginning of their first semester. Therefore, Pinyin is also significant to international students, holding a position in the field of Second Language Acquisition.

To sum up, Pinyin is of importance to both first and second language acquisition, which gives it a special status. Compared with studies of Chinese characters, fewer research studies have been conducted on the mechanisms of Pinyin, including recognition and production. This paper demonstrates that existing studies primarily focus on behavioral aspects, while a few are from a neurophysiological perspective, leaving room for further research. A triangular comparison among Pinyin, Chinese characters, and English can complete the comparison of Chinese and English, which is helpful in both first and second language acquisition.

Although Pinyin is significant in the cognition of Chinese, studies have focused more on behavioral aspects (such as error analysis and teaching interventions) than on neurological perspectives (such as EEG and fMRI). The comparison among Chinese characters, Pinyin, and English has not yet been conducted, which limits our understanding of the similarities and differences across languages. Additionally, the advantages of neurological methods, including temporal and spatial accuracy, enable us to study from more nuanced perspectives.

In this paper, we reviewed some studies on Hanyu Pinyin and discussed the achievements and shortcomings of previous studies, then proposed potential future research directions. The current paper aims to answer the following questions:

- What are the achievements and limitations of previous studies on comparing Chinese and English processing mechanisms from behavioral and neurological perspectives?
- What are the neural mechanisms of Pinyin processing?
- What future directions can be referenced in studying Pinyin's role in cognitive science and linguistics fields?

2 Methods and review subjects

The current paper used "Pinyin", "English", "Chinese", EEG, fMRI and so on as keywords to search through CNKI and Google Scholar. The paper first categorized the Pinyin-related references according to the research methods. Then sub-categorized the references according to the research subjects such as Chinese characters-English, or Chinese characters-Pinyin, or Pinyin-English.

Among the studies focused on the comparison of Chinese characters, English and Pinyin, there were abundant studies centering on the comparison between Chinese characters and English, and scholars such as Tan, Perfetti had done much effort on this direction. This kind of researches usually compared Chinese characters and English using EEG or fMRI methods, which lead to the findings about processing time course or activation locations in native Chinese speakers and non-native Chinese speakers. Due to the amount of this kind of references and lower relatedness to the current paper, we will not unfold these studies. This study selected Pinyin-related studies to emphasize the significance of Pinyin.

The paper first divided the references into behavioral and neurophysiological experiments. Then among the behavioral experiments, we sub-categorized according to the native language background of the subjects; in neurophysiological experiments we sub-categorized the references into fMRI and EEG studies.

3 Some studies on Hanyu Pinyin

Studies in this section mainly focused on the impact of Pinyin on L1 and L2 acquisitions, and the influence of Pinyin on children in digital era.

3.1 Some studies explored the significance of pinyin on the acquisition of Chinese and English

3.1.1 Non-native Chinese speakers

There were several perspectives in the studies on the acquisition of Chinese by non-native Chinese speakers.

Studies researching the relationship between Chinese characters and Pinyin also focus on the position of these two components when international students acquire Chinese. Chung (2002, 2003, 2007) found that the position of Pinyin could affect students' acquisition. He thought that for Chinese learners, the best order of Pinyin, new words, and English expressions is (from left to right): new words, Pinyin, English expressions. This finding is helpful for the edition of textbooks, as current textbooks in mainland China typically place Pinyin at the top of new words or characters, rather than on the right side. Therefore, the effect of the position of Pinyin still needs more research.

Regarding the presentation method of Pinyin, Lee and Kalyuga (2011) found that partial on-screen Pinyin transcription is a practical approach for more experienced Chinese learners. However, among lower-level Chinese learners, the use of complete on-screen Pinyin transcription, partial on-screen Pinyin transcription, and no on-screen Pinyin transcription did not make a difference, indicating that the effect is based on language experience.

Shi's (2019)academic dissertation systematically investigated Pinyin's influence on Chinese vocabulary acquisition in English-Chinese bilingual learners by using a matching test. The results showed that Pinyin helps learners of Chinese vocabulary, especially beginners, in line with the findings of Hao and Yang (2021).

Chen et al. (2017) recruited two groups of Chinese learners with different Chinese proficiency levels (as measured by the HSK) to first make semantic judgments by reading a two-syllable Pinyin and then make color decisions by reading target Chinese characters (categorized into orthographically related and control ones). The results confirmed the existence of implicit orthographic priming; however, this effect was only observed in the more proficient Chinese learners, not in the intermediate learners, indicating that the priming effect is related to reading experience.

It should be noticed that language experience was an important variation in the studies on Chinese language learners. Besides English-Chinese bilinguals, Zhang (2017) included Arabic-Chinese bilinguals in the thesis, and tried to find out the influence of L1 background and other meta-linguistic and background variables on the learning of Pinyin and Chinese characters. The main results showed that an L1 background did influence phonological awareness, Pinyin spelling, and Chinese character writing. What should not be ignored is that the thesis discussed other factors, such as proficiency in Chinese, the length of time the subjects spent in China, and the previous languages they had learned, among others, in the context of learning Chinese literacy acquisition. Studies comparing Pinyin with other languages also exist, such as those comparing Pinyin with German and English (Wu, 2007).

It should be noticed that although studies between alphabetic languages and Chinese are abundant, language such as Japanese is also interesting for researchers. Both Zhang and Tamaoka (2023) and Ke (2024) used Japanese-Chinese subjects to do some investigations and provided empirical evidence for Pinyin's effect in the non-native Chinese learners.

Zhang and Tamaoka (2023) instructed Japanese-Chinese subjects to do a paper test and a naming experiment. By coming up with the factors which influenced the pronunciation of Chinese words, Zhang and Tamaoka (2023) pointed out the using of cognates and non-cognates is an efficient way to compare Japanese and Chinese. More importantly, Zhang and Tamaoka (2023) used the exact same way to calculate the similarity ratio between Japanese and Chinese using by Zhang (2017), which offered a way to measure the object standard between two languages. The results were intertwined with cognate relationship between Japanese and Chinese, phonological similarities in words between Japanese and Chinese, Chinese language ability and distinction in script types, namely Pinyin and Hanzi (Zhang and Tamaoka, 2023). One thing should be concerned about was the conclusion which showed that as phonological similarity increased, the Reaction Time to name the words was slower with improved Chinese ability. This phenomenon displayed two interesting facets: one was that phonological similarities had negative effects (or inhibitory effect) on the naming time; the other was that more advanced Chinese learners had more difficulties in naming the Chinese words. These two factors need more future investigation.

Subjects with the same language background was also used in Ke's (2024) study. This study instructed 54 Japanese Chinese learners to finish a paper test, which tested subjects' Pinyin spelling ability, phonetic radical knowledge, semantic radical knowledge, single-character word meaning inferencing and contextualized multi-character word meaning inferencing abilities. The tasks were all based on the previous studies and lead to the result that Pinyin spelling facilitated single-character word meaning inferencing, and contextualized multi-character word meaning inferencing. In summary, Ke (2024) proved the facilitatory effect on self-teaching Chinese learning.

3.1.2 Native Chinese speakers

Studies focusing on the native Chinese speakers were more in China than abroad, probably because the universality of Pinyin.

Students in mainland China usually learn Pinyin in Grade 1 (approximately 6–7 years old). Some studies try to find out the relationship between Pinyin learning and Chinese acquisition or English acquisition (Chinese–English bilinguals), associating the relationship between phonological awareness longitudinal trajectories, tone awareness, with Pinyin proficiency, character learning in school-aged children or college students (Alison Holm, 1996; McBride-Chang et al., 2004; Shu et al., 2008; Wang and Gao, 2011; Ding et al., 2018; Xin et al., 2021).

Back in 1997, Giovannett (1997) had already emphasized this issue. In Giovannetti et al.'s book, the authors investigated native Chinese subjects who learned Pinyin before learning Chinese characters, as well as Hong Kong subjects who didn't learn Pinyin, both of whom learned English as their second language. And they included a group of native English speakers from Canada. The author assumed that subjects from mainland China would outperform those from Hong Kong in segmenting the speech stream into discrete phonemes, and Canadian English native speakers would outperform both Chinese groups. The results support their assumptions and demonstrate that learning Pinyin has a positive impact on the performance of English learners in segmenting phonemes in English, suggesting that this phonological awareness requires explicit training.

Similarly, Liu (1998) also realized the influence from Pinyin on English learning. Liu (1998) discussed the phonetic differences, grammatical structures, lexical interference, custom expressions, cultural background and native language context interference between Pinyin and English, and then came up with the pedagogical strategies. Liu mentioned that teachers should use comparative methods to teach Pinyin and English by comparing the pronunciations between Pinyin and English. Meanwhile, comparing similarities of the voiceless consonants and nasals in IPA with the consonants in Pinyin (Liu, 1998, p. 110). These strategies were the early examples of applying comparative methods between Pinyin and English.

We know that the Pinyin system is based on the alphabet used in English, so there are some graphemes that exist in both Pinyin and English, with some having the same or similar pronunciations. In contrast, some have different pronunciations, which is of interest. Li (2019) also mentioned this phenomenon in the article and found out that the English graphemes that also exist in Pinyin and share the identical pronunciations had the highest accuracy at the start of the learning point, while those that exist in Pinyin but have different pronunciations in the two languages appeared to be those associated with least improvement at the end of the learning process. According to Xin et al. (2021) study, a relationship exists between Pinyin and English, suggesting that Pinyin may interfere with the acquisition of English.

As more and more Chinese mainland schools teach Hanyu Pinyin and English simultaneously, the interference between Pinyin and English may become more pronounced. In fact, our interviews and some previous studies have already noted that Chinese children sometimes mix the pronunciations of English and Hanyu Pinyin, as seen in Wang (2020), indicating a negative transfer from Pinyin to English. While Wen (2021) study suggests that Pinyin helps students acquire English, indicating a positive transfer from Pinyin to English. Therefore, the relationship between Pinyin and English remains a matter of controversy in itself.

Specific notice should focus on Liu's dissertation (2010). Through interviews and questionnaires, Liu (2010) investigated 200 Grade 4 students and 30 English teachers in 6 schools in Mudanjiang, Heilongjiang Province. Results showed that most students and teachers were influenced by Pinyin in the process of learning and teaching process, while a only a few were not sure whether they were affected by Pinyin. After analyzing consonants and vowels, tones in Pinyin, and their similarities and differences between Pinyin and English, the author found out that positive transfer existed between Pinyin and English's consonants (Liu, 2010, p. 22). However, negative transfer appeared between the vowels between Pinyin and English (Liu, 2010, p. 22). Therefore, from Liu's investigation (2010), it showed that there did exist a bidirectional influence between Pinyin and English.

Besides, abundant studies related to Pinyin in China focused on Chinese native speakers' phonological awareness. Phonological awareness includes the awareness of syllables, the first and the last phoneme and phonology. In Chinese, besides these three layers awareness, there is tone awareness. Previous studies about phonological awareness explored the influence of Pinyin on Chinese character learning, word recognition, English spelling, bilingual reading levels (such as Zhang and Lin, 2002; Xie, 2003; Long and Ye, 2004; Xu and Ren, 2004; Dang, 2009; Pan, 2009; Dong and Lu, 2010; Guo, 2010; Liu, 2012; Bai, 2018; Yang, 2013; Chen, 2018). Studies also compared the differences and similarities between primary school students and college students (such as Pan, 2011). Among them, it should be noticed that in Dong and Lu (2010) and Xie's (2003) studies, they noticed the influence from L2 to L1, which was an intriguing topic in the bilingual processing models such as RHM (Revised Hierarchical Model). Moreover, Guo (2010) explored the phonological awareness of Pinyin in children in Yugan Dialectal district, which provided a new angle for studying the learning conditions in English and Chinese in other dialect areas (also see Xin et al., 2021). Other reviews can see Chen et al. (2016b).

Qiu's dissertation (2023), using native Chinese subjects to do 8 experiments focusing on Chinese characters and Pinyin representations in the Stroop paradigm. The results showed that semantic and phonological information can be activated when Chinese characters were written in Pinyin. And the mixed presentation of Chinese characters and Pinyin showed that Pinyin and Chinese characters influenced each other's performance in Stroop interference and facilitation effects (Qiu, 2023, p. i). What was interesting was that Qiu (2023) pointed out that although there were many theories and models about Chinese characters, there was no model or hypothesis focused on the processing of Pinyin words (Qiu, 2023, p. 25). We agree on this opinion and come up with the need to prove some models such as BIA+ model, RHM model and Assimilation/Accommodation Hypothesis in the Discussion section.

From Section 1.1 we found out that studies on Pinyin and English in China mainly emphasized on the phonological awareness. This type of study primarily employs contrastive analysis and error analysis approaches to conduct research, while mentioning less about bilingual cognition model (but see Xie, 2003, which mentioned BIA+ model). Nevertheless, the presentation of the neurological layer is of great interest in revealing the relationship between Pinyin and English.

3.2 The impact of Pinyin input on Chinese children's reading ability and neural performances in the digital era

Entering the twenty-first century, people rely more on digital products such as cell phones and computers than ever. These digital products bring more convenience to our lives and increase efficiency with more vivid pictures and keyboard input systems.

Back in 2013, Tan et al. (2013) discussed that the language input system in today's digital era can affect Chinese children's future reading development. In the article, Tan et al. (2013) investigated large numbers of children scattered in three cities in China and tested their character reading ability and Pinyin use. The results showed that children's reading ability is negatively correlated with the use of the pinyin input method, indicating that pinyin typing on devices hinders Chinese reading development (Tan et al., 2013). This phenomenon should not be ignored. Then, He et al. (2014) investigated a large sample of primary students in a mid-sized city in the mid-south region of China to detect the influence of electronic devices on children's developing dyslexia. In the article by He et al. (2014), the authors suggest that reducing the total time spent on digital devices and increasing literacy-related activities could protect children from developing dyslexia.

Additionally, Zhou et al. (2020) employed the fMRI method to investigate the neurodevelopment of reading in children aged 9–11 years. The results showed that the more frequent use of pinyin was associated with fewer activations in the left middle frontal gyrus, left inferior frontal gyrus, and right fusiform gyrus when children read Chinese characters. Additionally, the gray matter volume in the left middle frontal region was lower in children who used a more pinyin input system.

We know that the left middle frontal area is essential for Chinese reading, so this change cannot be ignored. Zhou et al.'s (2020) findings suggest that the pinyin input method in China can alter and affect neural development in children. Both Tan et al. (2013) and Zhou et al. (2020) mentioned that pinyin input through digital devices violates the traditional learning processes of written Chinese characters, which require visual orthographic analysis of characters and repeated handwriting. These three references stated that overusing digital devices has a negative influence on the reading acquisition of intermediate readers (those usually 9–11 years old). Still, another study (Chen et al., 2016b) suggests a different perspective.

As the subtitle presents, Pinyin has influence on both L1 (Chinese) and L2 (English) acquisition in native and non-native Chinese speakers. Not only does Pinyin have positive transfer on English, but also negatively affects English acquisition (Pinyin effect on L2 acquisition).

Moreover, from Tan and other scholars's studies in Section 1 we found out that Pinyin negatively influenced Chinese reading abilities, which meant Pinyin also affect L1 cognition (Pinyin effect on L1 acquisition). Therefore, from Section 1 studies showed Pinyin's role in language learning.

3.3 Odinye's study on the comparison between Pinyin and IPA

To the linguists, IPA (International Phonetic Alphabet) is well known for its accuracy in recording the vocal pronunciation of any language. Compared to Pinyin, IPA also uses a system with similarities and differences. The most direct comparison between Pinyin and IPA was done by Odinye (2015).

Odinye (2015) respectively introduced the histories of Pinyin and IPA. By summarizing the exact pronunciation and symbols using between Pinyin and IPA, Odinye (2015) compared consonants (initials) and vowels (coda) in detail, which presented a clear picture for readers and put a cornerstone for my study (in the process). In the meantime, Odinye pointed out the advantages and disadvantages of Pinyin and the reason why Pinyin hasn't became a orthography system, which is of importance for understanding the objective position of Pinyin in the mainland China.

Odinye's (2015) paper opened a window for us to compare Pinyin and English phonology in similar ways by mirroring the consonants and vowels one by one in the language phonology, and then finding similarities and differences between them. We will come back to this in the Discussion section.

4 The fMRI and EEG studies on Chinese characters and Pinyin processing

Compared to the Chinese and English comparison studies mentioned above, there are fewer studies on the comparison between Chinese characters and Hanyu Pinyin than those comparing Chinese characters with English. Since both characters and Pinyin can represent Chinese words (Fu et al., 2002), the familiar and different brain areas of reading characters and Pinyin are intriguing topics in recent years.

4.1 fMRI studies revealed differences between Chinese characters and Pinyin processing

Studies have shown that Chinese character reading activates the bilateral fusiform gyrus (Booth et al., 2006; Liu et al., 2008; Mo et al., 2015; Krafnick et al., 2016). These findings reveal the significant role of the fusiform gyrus and bilateralization in Chinese character reading, which differs from alphabetic language reading. Other studies studied the Chinese character processing mechanism from the frequency factors, the performance of the nouns and the verbs, to writing condition (Kuo et al., 2003; Li et al., 2004; Yang et al., 2011, 2019), which all provide us with new findings in Chinese character reading and writing. In this section, we will focus on those that are relevant to the comparison of Chinese characters and pinyin.

Noteworthy is the direct comparison between Chinese characters and pinyin, as well as research on pinyin. In fMRI studies, Chen et al. (2002) used fMRI to study the brain areas and mechanisms when native Mandarin speakers performed the task. The subjects are asked to decide whether paired Chinese characters or Pinyin, visually presented in front of them, "sounded like" a word. The results indicate that common areas are activated when subjects read both Chinese characters and Pinyin, including the superior, middle, and inferior temporal gyri, as well as the superior and inferior parietal lobes. However, different activation areas are observed when reading them separately. They also found that the written scripts could activate corresponding regions, and the relationship of scripts and activation areas between them, such as the inferior parietal cortex for Pinyin and the fusiform gyrus for Chinese characters.

Fu et al. (2002) used fMRI to study whether different written forms can affect the processing of words. In the experiment, native Chinese speakers are required to read silently the characters or Pinyin by presenting the stimulus at different rates (slow or fast). The results showed that although similar brain activation areas were observed when subjects read characters and Pinyin, the bilateral condition was more pronounced when they read Chinese characters (including the occipital-temporal cortex, superior and middle frontal gyri). In contrast, Pinyin reading activated the left middle frontal gyrus more. Besides, the rate effects in reading characters and Pinyin also activate different areas.

Besides comparing Pinyin and Chinese characters, Xu (2008) conducted a systematic fMRI study of Pinyin, utilizing fMRI to detect the distributions of activation areas when subjects read Pinyin. The experiment used real and pseudo-Pinyin as stimuli and instructed the subjects to read silently as soon as they passively viewed the stimuli, while the fMRI data was recorded. The article shows that, after comparing the common and different activation areas, the author concluded that reading real Pinyin and pseudo-Pinyin activated approximately the same brain areas. It is worth noting that Xu (2008) cited previous studies indicating that the left middle frontal gyrus (LMFG) plays a role in allocating resources for complex recognition in Chinese. He mentioned that the anterior part of the left middle frontal gyrus (BA10) was responsible for the detailed analysis of the radicals and strokes of Chinese characters in the spatial domain. However, this explanation did not fit Xu's study. According to Xu's study, the stimuli were Pinyin rather than Chinese characters. Therefore, BA9′s role in the Chinese recognition processing mechanism needed more research. Moreover, in Xu's study, there was no evidence showing left or right lateralization. The author explained two possible explanations that lead to this phenomenon. First, passively viewing Pinyin did not require the same degree of semantic processing as Chinese characters. The second explanation was that the subjects remained in a state where reading Pinyin was akin to learning a new language, leading to bilateralization at the beginning, similar to Qin et al.'s (2016) explanation. However, we doubt the latter account. Xu (2008) summarized that both hemispheres contribute to the processing of Pinyin, but the specific mechanism still requires further investigation.

Lin et al. (2007) employed dictation for mental writing tasks (also referred to as imagined/implicit writing) and observed that the activation areas for writing Chinese characters and Pinyin were similar. The other specific activation areas are listed in Supplementary Table 1.

There are a series of studies emphasizing the role of writing and its correlation to Chinese reading ability, represented by Tan et al. (2001b, 2003, 2005a,b); Cao et al. (2013a,b,c); Cao and Perfetti (2016) and Yang et al. (2019). A previous study by Cao et al. (2013a,b,c) found that character training led to higher accuracy in the lexical decision task and greater activation in the bilateral superior parietal lobules and sensorimotor cortex, compared to training through pinyin writing. Once again, the left middle frontal gyrus (LMFG) stands out. According to Cao and Perfetti (2016), the left middle frontal gyrus (LMFG) was activated more for character-writing-trained characters than for pinyin-writing-trained characters (Cao and Perfetti, 2016). Based on a series of studies, Cao et al. proposed that writing experience may add motor-related information to the orthographic system, thereby enhancing orthographic processing during reading.

Chen et al. (2016a) systematically reviewed the studies about the mechanisms of processing Pinyin. In the article, the authors particularly reviewed several fMRI studies comparing the activation brain areas of processing Pinyin and Chinese characters, with not as much as those about other aspects of Pinyin studies (such as the presentation ways of Pinyin, etc.) (also see Guo et al., 2022, which concluded a review on the brain activation areas in reading Chinese in phonology, orthographic, semantic and syntactic perspectives).

We summarized the above studies relevant to Pinyin in the Appendix. The Appendix presents the details of the tasks, stimuli, and activation areas in different studies.

Based on the six studies on Chinese characters and Pinyin presented in the Appendix, we can conclude that the activated areas for Pinyin reading remain unclear and are under debate. These six studies are compared, and the common activated areas observed in all six studies are summarized as follows. According to the task types, we divided the six studies into four categories. (1) The activation areas when people process Pinyin. First is the silent reading task (Fu et al., 2001, 2002; Xu, 2008): although the three studies using the same task have observed several areas, there is only one area that all three studies have mentioned: the left middle temporal gyrus (MFG). This suggests that the left middle temporal gyrus plays a crucial role in reading Pinyin. Its functions in reading Chinese are detailed in Cao and Perfetti (2016). Second is the lexical decision task (2002; Cao et al., 2013a,b,c), which mentions no common areas. It seems that using the same task type can still produce different activation areas when people process Pinyin. Third, there is implicit writing, also known as mental writing or imagined writing. By comparing Cao et al. (2013a) and Lin et al. (2007), we found that the results differed. Cao et al. (2013b) mentioned only the right inferior frontal gyrus, while Lin et al. (2007) observed many more activation areas besides the right inferior frontal gyrus when mentally writing Pinyin. Fourth, He et al. (2003) concluded the functional circuits of reading aloud Pinyin with or without semantics and silent reading Pinyin. The functional circuits of these processing mechanisms mainly involve Broca's area, Wernicke's area, and M1. Although there are factors that can explain the differences among these studies, the mechanism underlying Pinyin processing remains unclear. (2) The activation areas when people process Chinese characters. Because Xu (2008) conducted research solely on real and pseudo-Pinyin, which did not include Chinese characters, the studies by Chen et al. (2002); Cao et al. (2013a,c), and Lin et al. (2007) remain. We still categorize the studies by task types. First, Chen et al. (2002), and Cao et al. (2013a,c) used lexical decision tasks in processing Chinese characters. They displayed different areas with no overlap. Second, studies by Fu et al. (2001) and Fu et al. (2002) on silently reading Chinese characters overlapped in the superior parietal lobule, left posterior middle temporal gyrus, bilateral inferior temporal gyri, and bilateral superior frontal gyri. Third, Cao et al. (2013a,c) and Lin et al. (2007) employed implicit writing tasks to write Chinese characters, and both observed activation in the bilateral superior temporal gyri. Furthermore, in He et al.'s (2003) reading aloud task, there are differences between reading aloud and silent reading of Chinese characters. The former includes functional circuits among Broca's area, Wernicke's area, and SMA, while the latter only involves Broca's area and Wernicke's area, which can be explained since reading aloud behavior does require the involvement of the sensori-motor area. It appears that previous studies haven't reached a consensus on processing Pinyin. From Supplementary Table 1, we know that reading real Pinyin, pseudo-Pinyin, and characters can activate significantly different areas.

Studies aimed at detecting the activation areas in Chinese character reading are numerous, such as Tan et al. (2001a) and Tan et al. (2001b).

In summary, although some researchers have paid attention, fMRI studies relevant to Pinyin are significantly fewer than those studying the processing of Chinese characters. The neural connectivity and which brain areas function when processing Pinyin need further work.

4.2 EEG studies about Chinese processing mechanisms mainly focus on N170, P200, and N400

EEG methods are used more frequently in studying the mechanisms of language progression in Chinese. The topics of Chinese internality processing mechanisms are numerous, from the time course of processing orthography, phonology, and semantics of Chinese to the encoding of Chinese spoken words, which were explored in previous studies (Chen Baoguo, 2001, 2003; Chen Baoguo and Danling, 2006; Liu et al., 2011; Zhang and Wang, 2022). We will scratch a few of these research topics that are relevant to Chinese characters, especially Pinyin.

To trace the temporal dynamics of phonological consistency and phonetic combinability (orthographic neighborhood size) in the reading of Chinese phonograms, Hsu et al. (2009) used ERPs as the method. The results supported the phonological mapping hypothesis of the reading-related N170 effect. They revealed that the earlier stages of visual word recognition are shaped by the mapping of orthography to phonology, even in the Chinese language. The experiment also found effects in P200

TABLE 1 Summary of three studies about the processing of phonological, orthographical, and lexical information of Chinese characters in sentence contexts.

Author and Year	Stimuli	Components
Liu et al. (2003)	Graphically similar, homophonic, semantically related, and unrelated Chinese characters	P200, N400
Meng et al. (2008)	Correct characters, homophones, and orthographically similar Chinese characters	P200, N400
Liu et al. (2011)	Expected characters, homophonic, orthographically similar, synonyms, and control Chinese characters	P200, N400

and N400 with changes in the consistency and combinability of the characters.

Several studies, as represented by Malins and Joanisse (2012), utilized ERP to investigate the influence of phonological similarity on the time course of spoken word processing in Mandarin Chinese. They focused on the phonological mapping negativity (PMN) and the N400. Using five mismatch conditions: segmental (hua1/hua4), cohort (hua1/hui1), rhyme (hua1/gua1), tonal (hua1/jing1), and unrelated (hua1/lang2), Malins and Joanisse (2012) showed that tonal and phonemic information is accessed as soon as they become available during the spoken word. Compared to English, the onsets and rimes are weighted similarly in Mandarin as in English. Mandarin syllables are processed incrementally, just like English ones. This study offered evidence from the tonal languages on spoken word recognition.

Another direction also attracts the attention of scholars. Studies on the processing of phonological, orthographic, and lexical information in Chinese characters within sentence contexts often employ similar experimental designs. We summarize some studies in Table 1.

For example, Liu et al. (2003) used four types of word pairs: graphically similar, homophonic, semantically related, and unrelated, and instructed native speakers of Chinese to perform a meaning or pronunciation task in Chinese reading, with ERP being recorded. The results showed that graphically related pairs produced a smaller P200 in the pronunciation task and a smaller N400 in the meaning task. Homophones produced reduced N400 with bilateral sources in the meaning task. They also concluded that phonological information is activated automatically, even when the task is not related to pronunciation.

Meng et al. (2008) used correct characters, homophones, and orthographically similar characters. Meng et al. (2008) found that in Chinese reading, orthographic information was more relied on compared to phonological details. However, Liu et al. (2011) pointed out that the processing of synonyms in Chinese sentence comprehension is interesting and designed their experiment accordingly. Liu et al. (2011) used expected characters, homophones, orthographically similar words, synonyms, and control conditions in Chinese sentences, while ERPs were recorded.

From these studies, we notice that they have mainly focused on P200, N400, and P600 (two late positive shifts in the reference) to study the processing of phonological, orthographic, and lexical information in Chinese characters within sentence contexts. The results suggest that P200 might be relevant to the early extraction of phonological information and represent immediate semantic and orthographic lexical access during silent reading. The increased N400 represented that phonological and orthographical information influence semantic integration in Chinese sentence comprehension. The P600 (two late positive shifts) suggested semantic monitoring, orthographical retrieval, and reanalysis processing.

From the above descriptions and Supplementary Table 2, we can conclude that when studying the phonological, orthographic, and lexical aspects of Chinese sentences, the focus often includes semantic judgment, and therefore, N400 is continuously analyzed. Additionally, we recognize that P200 is a component that warrants consideration when addressing phonological processing.

Besides these three elements' processing mechanisms, Yin et al. (2020) studied N200's performance in actual Chinese character writing by using the repetition prime paradigm along with imagined and actual writing prime tasks. The results showed that actual writing, not imagined writing, elicited the N200 enhancement effect, indicating that actual writing influenced orthographic processing in Chinese character reading. This influence may involve a different neural mechanism from reading.

In addition to P200 and N400, among the components, researchers are especially interested in N170. N170 is a harmful component of the ERP, which appears approximately 170ms after the stimulus of a human face, generated primarily from bilateral posterior temporal electrodes (Cao et al., 2013a,b,c; Tanaka, 2020). It is known to all that N170 is sensitive to objects, especially faces and words (Schendan et al., 1998). Previous studies have reached a consensus on the N170 (Rossion and Jacques, 2008), including its sensitivity to native alphabetic languages and objects, as well as other alphabetic languages, symbols, and letter strings, which are not the focus of the current paper. What is interesting is that when people read visual words in print, there always exists a larger N170, called word-N170, compared to objects (Maurer et al., 2005). Besides, word-N170 showed a more pronounced left-lateralization than face-N170 (Maurer et al., 2008) in alphabetic languages so far. Detecting the differences between word-N170 and face-N170 has become a new topic for research (Kim et al., 2004; Fu et al., 2012; Cao et al., 2014a,b), with some studies even tried to explore the differences between word-N170 and face-N170 from gender aspects (Ji et al., 2016; Zhu et al., 2018). Some researchers directly compared the face-N170 with the word-N170 when subjects read Chinese characters (Liu et al., 2009; Li et al., 2019), which initiated a stream of studies on Chinese characters using EEG.

As we know, in alphabetic languages, such as English, N170 is more left-lateralized than the right hemisphere (Tarkiainen et al., 1999; Bentin et al., 1999; Mercure et al., 2008; Cai et al., 2008; Maurer et al., 2008; Lin et al., 2011; Mercure et al., 2011). However, what is the pattern of the Chinese? Such a question leads to studies about the performance of N170 in Chinese reading.

It should be noticed that Qin et al. (2016) directly compared N170 during subjects' reading of Chinese and Hanyu Pinyin. They found that, in fluent adult native Chinese speakers, reading Chinese characters elicited a stronger, more left-lateralized N170 compared to a visual baseline (i.e., symbols). Additionally, this effect was attributed to familiarity with the written form, rather than the visual features, which the authors explained. It should be noted that, in the paper, the authors attributed the absence of a left-lateralized pattern when two groups of subjects read Hanyu Pinyin to the fact that they were both unfamiliar with Pinyin compared to the characters. We doubt this opinion. Qin et al. mentioned in the paper that although the Pinyin system was still used, the chances that adults came across it were far less than those of characters (Qin et al., 2016). The question is, is the frequency of Pinyin less than the characters? Since we always use Pinyin input to type characters on computers and mobile phones in daily life. Tan et al. (2013) and Zhou et al. (2020) both mentioned that the pinyin method is the most popular method used by Chinese people. If we aim to study the effect of Pinyin familiarity on learning, we can compare children and adults, or students learning Chinese at different levels.

Cao and Zhang (2011) focused on the development of the N170 and used Chinese characters, pseudo characters, and stroke combinations as stimuli. They asked 32 primary students in Grade 2 and Grade 6, as well as college students, to perform a content-irrelevant color-matching task. The main results are (1) The subtle N170 specialization for Chinese characters had not emerged in Grade 2 children; (2) Both Chinese characters and pseudo characters elicited larger N170 responses than stroke combinations in Grade 6 children and college students (adults), suggesting that by Grade 6, the subtle N170 specialization for Chinese characters associated with reading learning had already appeared.

Besides, Lu et al. (2011) discussed the dual route mechanism found in alphabetic languages and the differences between reading Chinese characters and alphabetic languages. Lu et al. used high-frequency, pseudo-Chinese characters and artificial characters in the experiment. They instructed 17 native Chinese speakers to judge the size of the stimuli presented on the screen while EEGs were recorded. They focused on the N170 and P320, discussing their sources in the article. They found the N170 appeared in the bilateral occipital-temporal area, and high-frequency characters elicited the strongest current source density at the left occipital-temporal area. They especially mentioned that the P320 was observed at the bilateral occipital-temporal area, but elicited a right-hemisphere advantage. Lu et al. (2011) proposed that the P320 component plays a role in the assembled pathway for reading Chinese characters. The experiment demonstrated the dual route mechanism by showing that the addressed pathway was crucial for reading high-frequency Chinese characters at 170 ms, and the assembled pathway played a significant role in reading pseudo-Chinese characters through radical spatial analysis at 320 ms. This finding differed from the assembled pathways in alphabetic languages.

Wang et al. (2011) did two experiments: an orientation judgment task and a one-back identity matching task to investigate the face-like N170 in reading Chinese characters. They found that the inversion effects for upside-down faces and compound Chinese characters were bilateral for latency and right-lateralized for amplitudes. However, for simple Chinese characters, only the latency inversion effects were significant.

Zhang et al. (2021) used the neural adaptation paradigm to investigate the N170′s role in Chinese character reading and found that: (1) The left N170 was sensitive to Chinese characters' phonological and semantic information, and the phonetic radical; (2) The right N170 was sensitive to characters' meaning and the semantic radical. Previous studies have found N170′s activation either on the right hemisphere (Hsiao et al., 2007), left-lateralized N170 (Zhao et al., 2012), or on bilateral hemispheres (Kim et al., 2004; Hsu et al., 2009). Therefore, this finding is of interest because it explains the performance of the bilateralization of N170 in Chinese character reading, which is driven by both phonological and semantic reasons. Of course, the different results among previous studies may result from different experiment tasks or stimuli, which is also mentioned in Zhao et al. (2012).

Zhou et al. (2014) studied pre-lexical phonological processing in reading Chinese characters with EEG methods. Using RADICAL-RELATED and SINOGRAM-RELATED primes, they focused on three components: N170, P200, and N400. The results showed that the pronunciations of radicals were activated pre-lexically in reading low-frequency sinograms. Additionally, a radical interference effect was found for N170, P200, and N400 responses, while a sinogram (Chinese characters) interference effect was observed only for N400. Based on a series of previous studies, this paper suggests that P200 indexes sub-lexical processing, while N400 indexes lexical processing, and this opinion is enlightening for us.

Yum et al. (2015) used four types of pseudo characters—Unique, Dominant, Subordinate, and Illegal positions—as stimuli and instructed the subjects to perform a character decision task. The results were: (1) Illegal items were distinguished from other pseudo characters within 100 ms, and larger P100 amplitudes at the left posterior region; (2) At the N170, Illegal items elicited smaller negativity than Unique items. Combined, the study demonstrated that the legality of a radical position was detected at the initial stage of visual processing.

We summarized the studies we mentioned about N170 in Chinese reading in Table 2.

Previous studies on N170 have raised an interesting question: N170 appears in the right hemisphere for face recognition, whereas it is located in the left hemisphere for alphabetic languages such as English. In Chinese character reading, N170 is observed on the bilateral fusiform gyrus. However, how about pinyin? Since there were not many studies researching whether Pinyin would elicit N170 component, and what is the pattern of N170 probably produced by Pinyin. Fortunately, Qin et al. (2016) had already studied relevant issues by comparing Chinese characters and Pinuyin, but further work is needed to understand the mechanism of processing pinyin fully.

From this Section 2.2, we found that in Pinyin processing, there existed a controversial debate on the activation locations in the brain. In EEG studies, N170, P200, and N400 component might play a role in Pinyin processing mechanisms. Nevertheless, these components might not be the only three indexes, while other components might appear as the experiment tasks and stimuli changing in the process, such as in our prior experiment N200 appeared.

By reviewing neurophysiological studies related to Pinyin in Section 2, we came up with the idea that in MRI and EEG studies, different stimuli, paradigms, and tasks can affect the results. In MRI studies there were different activation areas when processing Chinese characters and Pinyin while some overlaps did appear as well. In EEG studies, N170, P200, and N400 seemed to be representative. However, they might not be the only indexes that

TABLE 2 Some studies about N170 in Chinese reading.

Author and Year	Task	Stimuli	Components	Main results
Qin et al. (2016)	Read Chinese and Hanyu Pinyin	Chinese characters, Hanyu Pinyin	N170	Chinese characters elicited stronger left-lateralized N170
Cao and Zhang (2011).	Content-irrelevant color-matching task	Chinese characters, pseudo characters, stroke combinations	N170	N170 specialization appears by Grade 6, showing that Chinese characters and pseudo characters elicited larger N170 in Grade 6 and college students, but not in Grade 2 students
Lu et al. (2011)	To judge the size of the stimuli presented on the screen	High-frequency, pseudo-Chinese characters, and artificial characters	N170, P320	N170-role in addressed way-high frequency Chinese characters; P320-role in the assembled way- radical spatial analysis-pseudo-Chinese characters
Wang et al. (2011)	Orientation judgment task	Face images, Chinese compound characters	N170	There exists a face-like N170 performance when people read Chinese compound characters
	One-back identity matching task			
Zhao et al. (2012)	Content-irrelevant color-matching task	Chinese characters, cartoon faces, line drawings of everyday objects, and combinations of strokes in Chinese characters	The left-lateralized N170	A marginally significant left-lateralization N170, which differentiated Chinese characters from control stimuli
Zhou et al. (2014)	Semantic judgment	RADICAL-RELATED primes, SINOGRAM-RELATED primes, RADICAL-CONTROL primes, SINOGRAM-CONTROL primes	N170, P200, N400	A radical interference effect was found for N170, P200, and N400 responses, while a sinogram (Chinese characters) interference effect was found only for N400; The pronunciations of radicals were activated pre-lexically
Yum et al. (2015)	Character decision task	Four types of pseudo characters: Unique, Dominant, Subordinate, and Illegal positions	N170	Radical position legality was detected at the initial stage of visual processing
Zhang et al. (2021)	Exp. 1: Read each character silently and judge whether the fourth character begins with the consonant "g"	Based on Chinese characters with similar orthography, whether they belong to the exact pronunciation: • O+P- (e.g., 敏, 侮, 悔, 莓); • O-P+ (e.g., 妹, 枚, 镁, 莓); • O+P+ (e.g., 酶, 梅, 霉, 莓); • O-P- (e.g., • 淮, 崛, 郎, 莓).	P100, N170	N170 in the left occipitotemporal region was sensitive to the character's phonological processing; N170 in the right occipitotemporal region was sensitive to the character's meaning and the semantic radical, i.e., semantic processing
	Exp. 2: read each character silently and judge whether the fourth character begins with the consonant "j"	Based on whether the four consecutive Chinese characters belong to the same semantic category, there are four conditions: • O+S- (e.g., 狡, 狂, 猜, 狒); • O-S+ (e.g., 豹, 鹿, 羚, 狒); • O+S+ (e.g., 狮, 狼, 狐, 狒); • O-S- (e.g., 淮, 崛, 郎, 狒).		

should be noticed. In the Discussion part the paper will show another component: N250, which appeared in my prior experiment.

5 Discussion

5.1 Achievements and limitations of previous studies about the comparison of Chinese characters, Pinyin, and English

The comparison studies among Chinese characters, English, and Hanyu Pinyin are expressed in the above paragraphs. From the above, we can conclude that: First, fMRI research has found that the left fusiform gyrus is an important area for differentiating between reading Chinese and English. The difference is that when people read English, the left fusiform gyrus is activated, whereas reading Chinese characters activates both the left and right fusiform gyri bilaterally. Second, in correspondence with the fMRI's results, the studies using EEG mainly focused on the N170, P200, and N400 components, with the N170 being more representative, as it showed that the left N170 activates when people read English, but the bilateral N170 when reading Chinese characters. N170′s performance in Pinyin is much less studied, although Qin et al. (2016) compared N170 of Chinese characters and Pinyin reading and found that Chinese characters elicited stronger N170 compared to Pinyin. In fMRI studies, the activations related to reading Pinyin remain inconsistent (see Supplementary Table 1).

There have been significant achievements in exploring the mysteries between Chinese and English, as well as Chinese itself, over the past few decades, using neurophysiological methods.

First, researchers began to notice the significance of Hanyu Pinyin by comparing Chinese characters with their corresponding Pinyin. Pinyin also plays a significant role in the acquisition of Chinese and English, and most studies focus on behavioral aspects, aiming to detect Pinyin's influence on the phonological awareness of the subjects. Such studies will open a new door to Chinese research fields, providing a more comprehensive vision. After all, Pinyin is an integral part of our lives.

Second, previous studies make us understand other factors that may affect the results, such as proficiency (Reiterer et al., 2009; Chang and Wang, 2016; Wang, 2018), fast and slow learners, for example, Maurer et al. (2006), cultural background (Peng et al., 2010), Age of Acquisition (Xue et al., 2017; Yum and Law, 2019) and so on. These findings offer us the opportunity to gain a deeper understanding of second language acquisition.

However, there still exist limitations to the previous studies. First, there are more studies on the comparison of Chinese characters and English, as well as studies comparing Chinese characters and Pinyin. Nevertheless, the studies that directly compare or discuss the relationship between Pinyin and English are even fewer. The ones we have are mainly behavioral studies. Therefore, there is still room for us to explore this direction using neurolinguistic methods. As Guan et al. (2011) pointed out, the most direct comparison is between Pinyin and English, which still lacks sufficient recognition in previous studies.

Typically, when comparing Chinese and English, studies often focus on the differences between Chinese characters and English, as these two languages differ significantly in their written forms. However, from the above description, we know that Pinyin is also a part of Chinese, in a way. Therefore, the most comprehensive comparison between Chinese and English should include Chinese characters, Pinyin, and the corresponding English translations. Based on this, we come up with the following formula:

Chinese vs. English = Chinese characters vs. English + Pinyin vs. English.

Nevertheless, the research reality so far is as follows (Figure 1):

- √ Chinese characters vs. English.
- √ Chinese characters vs. Pinyin.
- √ Pinyin's role in the acquisition of Chinese and English (Mainly from behavioral aspects).
- × Pinyin vs. English.

Since Pinyin vs. English is absent, it means that the formula lacks a part, i.e., the comparison between Chinese and English is somehow incomplete. We agree that to understand the processing mechanisms between Chinese and English fully, studies on Hanyu Pinyin, including comparisons between Pinyin and English, are indispensable.

What is interesting is that there was already an article comparing Chinese Pinyin with IPA (International Phonetic Alphabet) (Odinye, 2015), which enlightened us for studying the characteristics of Chinese.

We already know that from Odinye's (2015) paper, there are similarities and differences between Pinyin and IPA systems by comparing and summarizing the consonants and vowels one by one in tables. This could be used on the comparison between Pinyin and English, and this has already been used in our study (in the process). Since Pinyin is a romanization system, it overlaps with English alphabets somehow, on the pronunciation and orthography. However, the same letter form may pronounce differently in Pinyin and English, which causes confusion sometimes. The processing mechanisms behind the direct comparison between Pinyin and English then become conspicuously significant, because on the one hand, this direct comparison complete the triangle among Chinese characters, Pinyin and English, on the other hand, it has its pedagogical meanings for native Chinese children learning English and non-native Chinese learners.

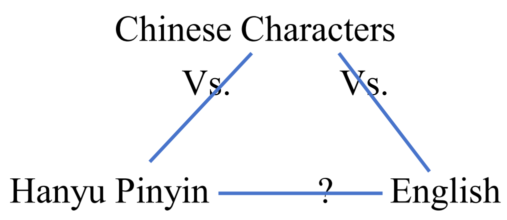

FIGURE 1
Diagram showing a triangular relationship among Chinese characters, Pinyin and English. Lines labeled "Vs." means there have already related studies comparing the two elements. A line with a question mark means there is a gap between Pinyin and English comparison.

Second, in the process of learning Chinese, previous research on the phonological production of Chinese learners consistently mentions that when international students acquire Chinese, there is interference from Pinyin. However, these studies did not inform people about how, or whether, there is interference, nor did they elucidate the mechanisms behind it. For example, Deng (2019) mentioned the interference of Pinyin, but only used one page (pp. 69–70); Bi's (2011) paper only used two pages to describe the inconvenience of the written Pinyin to international students; Zheng (2020) mentioned that the way the alphabet is written can have an impact, but only on one page. These studies have all observed the relationship between Pinyin and acquisition, albeit in a relatively straightforward manner, without providing further research or explanation. For example, they all mentioned that Pinyin might interfere with English; then, what is the pattern and what is the mechanism behind this phenomenon?

5.2 Theoretical and pedagogical significance of the triangle comparison among Chinese characters, Pinyin, and English

5.2.1 Prove and extend the assimilation/accommodation hypotheses, BIA+ and RHM in theoretical perspectives

Empirical evidence should help prove or disprove the hypotheses, theories, or models we developed.

When it comes to Chinese, we often come across Chinese characters. In fact, numerous studies have investigated the recognition of Chinese characters, including the activation of brain areas during processing and the comparison with English (Tan et al., 2001a,b; Tan et al., 2005a). Moreover, based on this, Perfetti came up with the Assimilation/Accommodation Hypothesis (Perfetti et al., 2007). The hypothesis proposes the brain's two processes of learning a second language: assimilation refers to the process by which learners utilize the brain areas and correlates they use to process native languages to acquire their second languages. For example, native Chinese use approximately the same brain areas when they read Chinese or English. Accommodation refers to the process that learners use to acquire a new second language in new areas. Through a series of research (Nelson et al., 2009; Cao et al., 2013a; Sun et al., 2015; Cao, 2016), the empirical data supported Perfetti's hypothesis and proved its validity. Nevertheless, being a romanization system, whether Pinyin processing activation areas are similar to Chinese characters and English remain unknown. Xu (2008) provided us with the results of activation areas of Pinyin alone, and in Section 2 we reviewed the processing mechanisms between Chinese characters and English. Does processing Pinyin activate the new area beside areas processing English, or existing areas similar to English? The comparison between Pinyin and English may display the Assimilation/Accommodation Hypotheses from a different angle.

Another widespread model about bilingualism is Dijkstra and van Heuven's BIA+ model van Heuven and Dijkstra (1998, 2010). Abundant recent or previous studies have already supported the BIA+'s non-selective access from alphabetical languages (for example, Kerkhofs et al., 2006; Kevin and Dijkstra, 2010; Vanlangendonck et al., 2019; Dijkstra et al., 2010 and so on, we could not list all the references here due to limited space, see more in van Heuven and Dijkstra, 2010), or from ideological languages such as Japanese Kanji (for example, Miwa et al., 2014; Nakayama et al., 2016 and so on). We thought that the direct comparison of the triangle among Pinyin, Chinese characters, and English may be proper to test the existing theories, aiming to detect the universal and differences across languages.

Revised Hierarchical Model was come up with in 1994 by Kroll and Stewart (1994). RHM was originally used to explain the asymmetrical phenomenon observed in the translation task in late SLA learners. This asymmetrical phenomenon was that in translation task, the time cost from L1 to L2 (Forward translation) was longer than from L2 to L1 (Backward translation), which was closely related to the strength between lexicons and concepts in L1 and L2 in bilinguals. Nevertheless, it was pointed out by Kroll et al. (2010) that by combining the recent 15 years' empirical studies, they thought that BIA+ model could better explain the data in previous researches, because RHM was basically a model that aimed to the lexical production (bilinguals' performances in translation tasks) rather than lexical cognition (Kroll et al., 2010, p. 374). By comparing Chinese characters, Pinyin and English with specific experimental paradigms, such as lexical decision task, we can expend the perspectives from production to perception between logographic language and alphabetic language, which is a new window to peak through for RHM.

5.2.2 Provide empirical support to the pedagogical strategies

Since the 1950s, Hanyu Pinyin has become a cornerstone in helping eliminate illiteracy and educate Chinese people to read efficiently. Until now, it remains an important part of our educational life, not only in first language acquisition (such as the cognition of Chinese characters in children), but also in second language acquisition (such as phonological awareness training).

The triangle comparison among Chinese characters, Pinyin and English could provide some answers to questions such as whether children confuse Pinyin and English when learning them at the same time, or whether there exits interference between them, which are the main concern for Chinese parents and teachers. In our prior interview and investigation, we found that at least in south-eastern areas in China, children acquired Pinyin and English in Grade 1 (approximately in their 6 or 7 years old). Some children even know Pinyin and English in their preschools. Meanwhile, many parents expressed their concerns for whether their children could master both Pinyin and English well. We mentioned that in previous study (Liu, 2010) more than 80% students were actually under the influence on English learning from Pinyin. Therefore, it is significant to clear the specific confusion conditions and processing mechanisms between Pinyin and English. For example, through empirical studies, we can decide particular textbooks and pedagogical strategies from differences and similarities between Pinyin and English, which is important in decreasing the confusions in children.

Moreover, in Teaching Chinese as a Foreign Language, Pinyin is also required to be mastered by Chinese learners in order to learn Chinese better. Whether there is influence between Pinyin and English is significant to Chinese learners whose native language is alphabetic language. Figuring out the mechanisms of Pinyin and English processing can provide empirical support for textbook design of different language background. Meanwhile, the comparative results between Pinyin and English will extend the achievements between Pinyin and other languages.

It should be noticed that the comparison between Chinese and English should also consider the actual using conditions. Although Pinyin is not an official language or writing system in China, it is often used in our daily life, which consists of an important part in people's lives. We have already known that there are differences and similarities between Chinese characters and English, Chinese characters and Pinyin which can be explained by several bilingual models, therefore the study between Pinyin and English can complete the triangle structure of Chinese–English comparison in both theoretical and pedagogical perspectives by showing the mechanisms of Chinese and English processing are not the only ways which have already appeared in previous studies.

6 Future research directions

Previous studies have already explored the relationship between Chinese characters and English, with some comparing Chinese characters and Hanyu Pinyin (Chen et al., 2002; Fu et al., 2002), as well as Xu (2008). However, there has been a lack of comparison between Hanyu Pinyin and English, with only some behavioral studies. One possible justification for the lack of Pinyin study is that it is less used in daily life, making it less important to regard the Pinyin system as a factor. In fact, students in China have been learning Pinyin since primary school. However, currently we have not found enough studies that directly compare pinyin and English using EEG or fMRI, which leaves space to explore in future research. For example, from the above, we can find out that N170 seems to be an important index in research. That is what we need to focus on in future work by designing appropriate experimental paradigms and stimuli, which is also our current focus.

In section 2 we mentioned that N170, P200 and N400 may not be the only three indexes that matter in language processing. As a matter of fact, the author had already designed an experiment for Chinese–English subjects and did a prior experiment. The prior experiment used masked priming paradigm, and asked Chinese–English bilingual adults to do a lexical decision task while EEG was recorded. The stimuli used in the prior experiment were design by specific matching conditions from orthographic and phonological perspectives for Pinyin and English referenced from previous studies. The results were interesting. There were differences among different matching conditions in Reaction Time and Accuracy. Moreover, the N250 component was found in the temporal-occipital area. From previous studies we knew that N200 was related to the repetition effect (such as in Lv et al., 2008), or orthographic and phonological processing in sub-lexical layer, such as Carreiras et al. (2009a), Carreiras et al. (2009b). N250 component was observed in other previous studies such as Zhang et al. (2013), Wong et al. (2014), Nie et al. (2016), Luo et al. (2016); or in studies using faces as stimuli such as Pierce et al. (2011), Schweinberger and Neumann (2016). However, the role and mechanisms of N250 component was under debate without clear explanation. Why in the prior experiment there appeared N250 in Pinyin-English processing? Was it coincidence, or did N250 really meaning something other than effect appeared in faces stimuli? Therefore it is conspicuous that the mechanisms of processing Pinyin and English are somewhat different from Chinese characters and English.

Extending the applying perspectives of the BIA+ model and RHM to other layers can also lead to future researchers. The author had already undergo other experiments to provide support from lexical production by changing directions of L1 and L2 and by different tasks. All these results can prove BIA+ and RHM in some way. In future studies scholars can also use different paradigms and tasks or use different modalities such as both visual and auditory ways.

Meanwhile, combining neurological methods with longitudinal studies within the same subjects learning Chinese or among different subjects with different Chinese (L2) proficiency will be a research-worthy topic for future researchers in the Second Language acquisition area. Previous studies have already shown that there exist differences within the same group learning L2 at different terms or among different grades learning L1, e.g., (Maurer et al., 2005, 2006; Liu et al., 2006; Cao et al., 2011; Sun et al., 2015) in brain activation areas and brain waves. In contrast, future research can focus on subjects with different Chinese proficiency levels and at different age stages to research a more comprehensive picture of the field. Some work have been already done such as Chen et al. (2017) in Section 1 focusing on proficient and intermediate Chinese learners.

Besides, relating adult Second Language Acquisition to children's neural network development is also research-worthy. As we can see, Pinyin plays a significant role in the process of learning Chinese characters among Chinese children. It is interesting to consider whether there are specific mechanisms in processing Pinyin. What is the complete process of learning Pinyin before and after Chinese characters?

There have already been some studies about children's development of neural networks (Maurer et al., 2005; Brem et al., 2006; Maurer et al., 2006; Brem et al., 2009; Spironelli and Angrilli, 2009; Cao et al., 2011). They explored the developing trajectory of N170 in preschool children, primary school students, adults, and older adults. However, we cannot see whether such a trajectory exists along the processes of learning Chinese at different proficiency levels. Further studies on this issue can be conducted and compared with previous research on children's neural network development, such as the development and neural changes from learning Pinyin to Chinese characters.

Whether there exists lateralization when people process Pinyin is also worth researching. Supplementary Table 1 shows that some studies have proved the existence of lateralization, while others have not. Further study is required to prove or disprove its existence and mechanism.

The influence of Pinyin typing on Chinese learning is also of interest to researchers. The existing studies have already noted the effects of Pinyin typing on Chinese reading abilities (see the above descriptions), leaving a gap for those who learn Chinese as a second language. Most studies have mentioned the adverse effects of Pinyin on Chinese learning. In contrast, some studies, such as Guan et al. (2011), have mentioned that Pinyin typing strengthens the relationship between phonology and Chinese characters, which is helpful for Chinese learning. The specific influence of Pinyin typing on Chinese acquisition still needs further research.

Another interesting question is the influence of Pinyin on Chinese children's neural development, i.e., the changes in children's brains when we typically use a Pinyin input system to express and convey our ideas and messages, and the role of Pinyin in acquiring Chinese for Chinese learners. Entering the digital era, people encounter electronic devices almost daily. Studies are investigating the impact of typing on reading and brain areas in alphabetic languages (Cunningham and Stanovich, 1990; Longcamp et al., 2008; Purcell et al., 2011). In China, as mentioned earlier in this article, people type Chinese characters using the pinyin system on mobile phones or computers. Our primary observation reveals that only a few people use the traditional handwriting system to type characters on electronic devices, with most individuals using the pinyin system through 26-key or 9-key pinyin keyboards. Both keyboard input methods are achieved by typing Hanyu Pinyin. Therefore, for both Chinese children and Chinese learners, the Pinyin input system has influenced their lives significantly in behavioral ways.

The above studies investigated Chinese students; how about foreign Chinese learners? In a recent survey, Harvey and Brooks (2022) assessed the effects of digital Pinyin writing by including 4th-grade students in an American Chinese immersion school. The results showed that children who participated in text messaging to learn Chinese gained less compared to those who learned Chinese through traditional pencil-and-paper word work. Harvey and Brooks (2022) noted that we should be cautious when introducing digital Pinyin input into the Chinese language arts curriculum. Besides these studies, Siok and Liu (2018) also provide an example of detecting the influence of Pinyin input on bilingual students, leaving us with more space to explore.

Moreover, previous studies related to different language background enlightened us that we should be attention to the abundant language background of foreign students. In Section 1, Wu (2007) and Zhang (2017), respectively, paid attention to German-Chinese and Arabic-Chinese bilinguals, which all used Chinese characters as experiment materials. Then what is the condition between Pinyin and German, or Arabic? What are the differences of processing Pinyin and Japanese, since Japanese has kanji and kana. And what are the differences and similarities between Pinyin and Korean processing? These are the questions remain to be revealed in the future.

7 Conclusion

The current paper primarily presents studies comparing Chinese characters, English, and Pinyin over the past decades, utilizing fMRI and EEG. We found that in fMRI, there are common and different activation areas when people process Chinese characters, English, and Pinyin. In EEG studies, we identified N170, P200, and N400 as indices that warrant attention when exploring the phonological, orthographic, and semantic processes of reading Chinese and English. We also found that from a neurolinguistic perspective, the number of comparisons between Chinese characters and English, or Chinese characters and Pinyin, is much more than the comparison between Pinyin and English. We then presented the achievements and limitations of the previous work and identified future research topics.

According to previous studies, behavioral and neurophysiological methods are frequently employed in studies on Pinyin; however, most studies utilize behavioral methods, while fewer employ neurolinguistic methods.

The topics in studying the mechanisms of processing Pinyin are primarily approached from both inter-language and intra-language perspectives. It includes the processing of Pinyin alone, as well as the comparison between processing Pinyin and Chinese characters, such as the activation time course of phonology, semantics, and orthography when reading Pinyin, and the reading ability performance of Chinese characters, from both native Chinese children and Chinese learners. The comparison between processing Pinyin and English, such as the role of Pinyin in learning English, is also noteworthy. In a word, previous studies have aimed to investigate whether there is a relationship between Pinyin and the acquisition of Chinese and English. If there is, then what effects does it make? Facilitative or inhibitive influence? i.e., positive or negative transference. On the one hand, it investigates Pinyin's impact on Chinese acquisition, i.e., L1 to L1. On the other hand, it researched Pinyin, i.e., L1′s influence on L2 (English). Moreover, from the Chinese learners' view, there are bidirectional studying topics that can be topics to research, from L1 (English) to L2 (Pinyin) or L2 (Pinyin) to L1 (English).

Nowadays, with digital devices becoming an integral part of our daily lives, leading to the increased popularity of both Pinyin and Chinese character input, the need for a comparative analysis of Chinese characters, Pinyin, and English is even more urgent and valuable. The comparison between Pinyin and English can provide valuable insights for textbook editors. For example, how to avoid interference between Pinyin and English during teaching. In a word, the triangular comparison of these three elements can broaden our vision of the common differences between Chinese and English, and deepen our understanding of the mechanisms behind the processing of Chinese and English from a whole point.

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