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Recent Advances in Chinese Developmental Dyslexia

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Abstract

Chinese developmental dyslexia (DD) research provides important insights into the language-universal and language-specific mechanisms underlying dyslexia. In this article, we review recent advances in Chinese DD. Converging behavioral evidence suggests that, while phonological and rapid automatized naming deficits are language universal, orthographic and morphological deficits are specific to the linguistic properties of Chinese. At the neural level, hypoactivation in the left superior temporal/inferior frontal regions in dyslexic children across Chinese and alphabetic languages may indicate a shared phonological processing deficit, whereas hyperactivation in the right inferior occipital/middle temporal regions and atypical activation in the left frontal areas in Chinese dyslexic children may indicate a language-specific compensatory strategy for impaired visual-spatial analysis and a morphological deficit in Chinese DD, respectively. The findings call for further theoretical endeavors to understand the language-universal and Chinese-specific neurobiological mechanisms underlying dyslexia and to design more effective and efficient intervention programs.

1. INTRODUCTION

The development of proper reading skills is critical for personal success in our literacy-driven society. While infants are born to have the language instinct to listen and speak, the human brain is not naturally wired to read and write. It requires systematic and explicit instructions and practices to decode the meanings of printed words (Foorman et al. 1998). Regardless of orthographic variations across different writing systems, there are universal operating mechanisms and principles that regulate the perceptual and cognitive processes of connecting visual graphic input to the phonological structure of the spoken language (Verhoeven & Perfetti 2022). There are also shared phonological deficits associated with reading difficulties across languages (Verhoeven et al. 2019). Nonetheless, the unique properties of many nonalphabetic languages, such as Chinese, present efficient reading or reading difficulties that cannot be fully explained by theoretical and computational models based on alphabetic reading (Li et al. 2022). In this review, we discuss recent advances in Chinese developmental dyslexia (DD) research and future directions that can improve our understanding of the behavioral and neurobiological bases of dyslexia across languages and writing systems.

DD, which is also termed specific reading disability, is characterized by persistent (evident from the early school years and possibly lifelong) difficulties in acquiring basic reading skills such as accurate and fluent word reading and spelling, despite typical intelligence, adequate learning environments, and the absence of clinical sensory deficits (Leonard 1998, Snowling 2000). The dominant theoretical framework for dyslexia posits the existence of difficulty in phonological processing to map visual input onto the sound structures of the language for extracting meaning. Other theoretical accounts point to the extended nature of the phonological deficit, with its roots in sensory, motor, and learning processes, including visual theory, rapid auditory processing theory, cerebellar theory, and magnocellular theory (Ramus et al. 2003). Most early DD research focused on the English language, which is known for its complexity or lack of transparency with regard to various spelling rules and exceptions for letter-to-sound correspondences. For a long time, it was also believed that dyslexia was a problem that existed only in western languages in which alphabetic writing systems were widely used and that its occurrence rate was extremely low among Asian populations, especially Chinese, due to its nonalphabetic writing system and lack of correspondence between orthography and phonology (Makita 1968, Rozin et al. 1971, Kline 1977). However, this belief does not reflect the reality of Chinese reading. Both nonalphabetic Chinese reading and alphabetic English reading have orthography–phonology correspondence. Chinese and English differ only in the orthographic/phonological units: the character/syllable in Chinese versus the grapheme/phoneme in English. The low rates of diagnosis of Chinese DD in the past might also reflect the cultural influences of traditional Confucianism, according to which parents and teachers tended to attribute children's reading underachievement to lack of effort, motivation, or aptitude. In the early 1980s, the existence of Chinese DD was clearly confirmed (Stevenson et al. 1982). Later, various studies and epidemiological surveys adopting diagnosis criteria similar to those in English reported consistently that there were similar prevalence rates for Chinese DD (approximately 4–10%) as for alphabetic language communities (approximately 5–10%) (Zhang et al. 1996, Chan et al. 2007, Sun et al. 2013, Lin et al. 2020; see Yang et al. 2022 for a meta-analysis). Interestingly, the prevalence rate for Japanese morpho-graphic Kanji (the Japanese form of Chinese characters) DD is approximately 6.9%, in sharp contrast to the 0.2% prevalence rate for Japanese syllabic Hiragana DD (Uno et al. 2009). Pooling together cross-linguistic evidence has become an indispensable and standard tool for examining the relative strengths and weakness of individuals with dyslexia and identifying language-universal and language-specific cognitive principles to account for normal reading development and its breakdown in contrasting orthographies and to inform theory and practice (Verhoeven et al. 2019).

In the past two decades, there has been a surge of interest in Chinese DD. Studies have focused on three main aspects of Chinese DD: its linguistic profiles (Ho et al. 2004, Shu et al. 2006, Cheung et al. 2009, Li & Ho 2011, Liao et al. 2015, Tong et al. 2019, Lin et al. 2020, Cheng et al. 2021; see Peng et al. 2017 for a meta-analysis and McBride-Chang et al. 2018 for a review), neural mechanisms (Siok et al. 2004, 2009; Hu et al. 2010; Chung et al. 2012; Zhang et al. 2012; Cao et al. 2017; Su et al. 2018; Feng et al. 2020; Zhang et al. 2021; see Yan et al. 2021 and Li & Bi 2022 for meta-analyses), and genetic bases (Su et al. 2015, Kong et al. 2016, Sun et al. 2017, Waye et al. 2017). Significant strides have been made in understanding the linguistic and neurogenetic deficits underlying Chinese DD and thus the language-universal and language-specific properties of dyslexia across languages. Furthermore, researchers have developed various training and intervention programs that have been somewhat useful in improving the reading and reading-related skills of dyslexic children (Chow et al. 2008, Dai et al. 2016, Wang 2017, J. Zhao et al. 2019, Wang et al. 2021, Zhang et al. 2021). Given the number of reviews on reading and dyslexia, in this article we focus on the recent advances in studies on Chinese DD and point out the current limitations and future directions. We begin with an introduction to the characteristics of Chinese orthography, phonology, and morphology, followed by their roles in typical reading acquisition to better understand the linguistic profiles and treatment of Chinese DD.

2. DISTINCT CHARACTERISTICS OF CHINESE ORTHOGRAPHY, PHONOLOGY, AND MORPHOLOGY

Reading is the process of constructing meaning from print; during this process, access to phonological representations of printed words is essential in all languages (Frost 1998, Ziegler et al. 2000). Therefore, the properties of orthography, phonology, and morphology (meaning) and the relations between them play important roles in reading acquisition and manifestations of reading impairment.

Chinese orthography has distinct features that are not found in Indo-European languages like English. Specifically, Chinese adopts a logographic writing system, which is completely different from the alphabetic system. The basic unit of Chinese script is a character. A Chinese character differs from an alphabetic word at least in two aspects. First, each character is composed of strokes. Strokes are horizontal, vertical, or slanting lines; are quite different from graphemes in appearance; and are unpronounceable. There are six basic strokes (i.e., 一, 丨, 丿, ㇏, 丶, ㇀) in the simplified and traditional Chinese scripts. Second, basic strokes are combined to form more than 50 stroke patterns (e.g., ㇝, ㇇, ㇅), approximately 200 larger components (e.g., 讠, 刂, 扌), and eventually characters (e.g., 写, 汉, 字) in a square-shaped space, in contrast to the linear structure of an alphabetic word. There are approximately 3,000 simplified characters commonly used in Mainland China and approximately 4,500 traditional characters frequently used in Taiwan, Hong Kong, and Macao. The average number of strokes of the 2,000 most commonly used simplified and traditional characters is 9.0 and 11.2, respectively (Chan 1982).

The nonalphabetic strokes and nonlinear overall spatial configurations make Chinese characters visually compact and complicated. On the basis of the multidimensional measure of graph complexity, Chinese script has the greatest visual complexity among 131 writing systems (Chang et al. 2016, 2018). In many cases, there are subtle visual differences between characters. For example, 戍 (to defend), 戊 (the fifth of the ten Heavenly Stems), and 戌 (the eleventh of the twelve Earthly Branches) are characters with completely different meanings.

Beyond basic visual complexity, Chinese characters have internal structures that are fairly predictable. Except for a small number of single-component characters, approximately 80–90% of simplified and traditional Chinese characters are pictophonetic compounds, with each compound comprising a semantic component and a phonetic component (Ho & Bryant 1997). The component is also referred to as a radical, which is a stroke pattern or a combination of stroke patterns under which the character is traditionally listed in a Chinese dictionary. Semantic radicals convey information about meaning, and phonetic radicals carry information about pronunciation, although the script–meaning and script–sound regularities differ to some degree, with the semantic radicals being functionally more reliable than the phonetic ones (Shu et al. 2003). For example, the pictophonetic character 材 (timber) is composed of the semantic radical 木 (wood) and the phonetic radical 才. The semantic radical is directly linked to the meaning of the character, and the phonetic radical has the same pronunciation as the compound character. The orthographic rules in Chinese are complicated. However, most semantic radicals and some phonetic radicals consistently appear in the same position across characters (Feldman & Siok 1999). For example, the semantic radicals 冖 and 宀 always appear at the top of a character, while the semantic radicals 氵 and 亻 always appear on the left side of a character. The positional regularity of radicals mostly determines the lexicality of the orthographic structure (Shu et al. 2003). If a radical appears in a legal position that is consistent with orthographic rules, the character is considered to be a real character/pseudocharacter, whereas if a radical appears in an illegal position that violates orthographic rules, the character is considered to be a noncharacter.

The most striking features of Chinese phonology that are different from Indo-European languages include a very simple syllable structure, the existence of lexical tones, and an abundance of homophones. Chinese phonology permits simple syllable structure, i.e., consonant + vowel + nasal, in which only the vowel is an indispensable part while consonant clusters (e.g., /st/ in the English word stop) are not permitted. A syllable can be decomposed into smaller subsyllabic units, i.e., onset and rime (e.g., /t/ and /an/ are the onset and rime in the word tan, respectively). Chinese is a tonal language in which pitch contours at the syllable level are used to distinguish lexical meanings from otherwise identical strings of phonemes, in sharp contrast to nontonal languages such as English, in which pitch variations are primarily used to mark pragmatic meanings such as emotion and sentence modality (Wang 1973, Ho & Bryant 1997). That is, Chinese lexical tones have phonemic status. The four lexical tones in Mandarin Chinese are described phonetically as high-level tone (tone 1), mid-rising tone (tone 2), low-falling/rising tone (tone 3), and high-falling tone (tone 4). For example, whether the syllable /yi/ (transcribed in Chinese Pinyin, an alphabetic coding system) means one, aunt, chair, or a hundred million depends on whether it is spoken with tones 1, 2, 3, or 4, respectively. There are only approximately 400 syllables in Chinese, and the total rises to approximately 1,200 when syllables are further differentiated by tone. Due to the limited number of syllables in Chinese, most syllables share homophones. It is estimated that on average every syllable has five homophones with different meanings (Packard 2000). The exact meaning of each syllable, therefore, is clarified only in a compound word. For example, there are four homophones for the toned syllable "xia 4" (the number signifies lexical tone). Its meaning becomes clear only in compound words, such as "xia 4 tian 1" (the summer season), "xia 4 qu 4" (to go down), "xia 4 ren 2" (frightening), and "xia 4 men 2" (the name of a city).

The most salient feature of Chinese morphology is the correspondence between morpheme (the basic semantic unit), syllable (the basic phonological unit), and character (the basic orthographic unit). Chinese is sometimes described as a morphosyllabic language in which each morpheme is represented by a syllable as well as a character. Morphological information, therefore, plays vital roles in both spoken and written Chinese. In addition to the many homophonic syllables, as described above, there are also a large number of homographic characters. For example, the character 面 represents two morphemes: 面孔 (face) and 面粉 (flour). The exact meanings of the homophonic syllables and homographic characters become disambiguated in different compound words. Furthermore, most words in Chinese are bisyllabic and multisyllabic, with bisyllabic words accounting for approximately two-thirds of all words (Taylor & Taylor 1995). Bisyllabic and multisyllabic words are commonly built on single-syllabic words. The meaning of the whole word is often formed by integrating the meanings of individual morphemes. For example, the word 教室 (classroom) is built from 教 (to teach) and 室 (room). Therefore, Chinese words are semantically transparent (Shu et al. 2006). Similar examples exist in English. For example, the compound word fingerprint is made up of the two morphemes finger and print. However, such examples are much less frequent in English than in Chinese.

Thus, there exist language-specific properties in Chinese orthography, phonology, and morphology that do not resemble those in the alphabetic languages. Researchers have been interested in exploring whether all the properties mentioned above—specifically the visual-spatial complexity of Chinese characters, the simplicity of syllable structure, the existence of lexical tones, and the extensiveness of compound words—contribute to normal reading and its breakdown in reading disorders.

3. RELEVANCE OF LINGUISTIC FEATURES TO READING ACQUISITION IN TYPICALLY DEVELOPING CHILDREN

How the linguistic features of Chinese may affect reading acquisition in typically developing children has been examined in many previous studies, indicating that children's sensitivities to various linguistic features contribute to reading. In particular, visual skills and orthographic knowledge, phonological awareness (PA), morphological awareness (MA), and rapid automatized naming (RAN) have been identified as the core abilities for children to acquire literacy in Chinese (Ho & Bryant 1999, McBride-Chang et al. 2003, Shu et al. 2008, Li et al. 2012, Xue et al. 2013, Cheng et al. 2016, Y. Zhao et al. 2019; see McBride-Chang & Wang 2015 for a review). Given the visual complexity of Chinese characters, essential visual skills, which are defined as the ability to visually process two-dimensional representations of shapes and lines (Li et al. 2012), encompass both basic visual-perceptual skills (e.g., visual form identification and discrimination and visual-spatial relations) and visual memory (Yang et al. 2013, Zhou et al. 2018). The association between visual skills and Chinese reading is moderate, with a significant correlation usually found in children of kindergarten and lower-grade ages, but not in children of upper-grade ages (Chen & Wong 1991, Ho & Bryant 1999, Siok & Fletcher 2001, McBride-Chang et al. 2005, Li et al. 2012; see Yang et al. 2013 for a meta-analysis). By contrast, orthographic knowledge, i.e., an understanding of the conventions used in the Chinese writing system such as stroke sequences and radical positions, is significantly associated with reading and writing Chinese characters in children of upper-grade ages (Ho et al. 2001, Siok & Fletcher 2001, Lau & Leung 2004, He et al. 2005, Li et al. 2012). These results indicate that the relative importance of visual skills and orthographic knowledge to Chinese reading depends on the developmental stage. Specifically, younger children are sensitive to the salient features of Chinese characters at the perceptual level, while older children with more reading experience utilize orthographic knowledge to recognize Chinese characters.

The strong association between PA and reading in alphabetic languages has long been established (Gottardo et al. 1996, Hulme et al. 2002, Ziegler et al. 2010). In contrast to alphabetic languages, in which segmental phonemic awareness plays a major role throughout reading acquisition, various phonological units have the dominant role at different developmental stages of Chinese reading. Specifically, syllable awareness is uniquely associated with Chinese character recognition in kindergarten children; then rime awareness becomes important in reading in lower-grade children; and lastly, phoneme awareness begins to play a role in upper-grade children (Ho & Bryant 1997, McBride-Chang & Ho 2000, Siok & Fletcher 2001, McBride-Chang et al. 2004, Chow et al. 2005, Shu et al. 2008, Li et al. 2012, Pan et al. 2016; see Song et al. 2016 and

Ruan et al. 2018 for meta-analyses). The importance of PA to Chinese reading exists irrespective of whether simplified (used in Mainland China) or traditional (used in Taiwan, Hong Kong, and Macao) Chinese scripts are adopted or whether alphabet-based transcription systems are used to help children learn the pronunciation of a character (two different systems are adopted in Mainland China and Taiwan, but there is no such system in Hong Kong and Macao). These results indicate that PA by itself is important for Chinese reading, although phonetic information is not explicitly represented in the Chinese script. Furthermore, sensitivities to larger phonological units such as syllables and rimes are better predictors of Chinese reading, especially in the earlier ages, as implicated by psycholinguistic grain size theory (Ziegler & Goswami 2005). Interestingly, lexical tone awareness is a good indicator of reading variability (McBride-Chang et al. 2008b, Shu et al. 2008), presumably because in many cases children have to rely on lexical tones to distinguish word meanings due to the large number of words sharing identical consonants and vowels but differing in tones.

MA in Chinese is usually assessed through three measurements that examine sensitivities to homophonic and homographic morphemes (the homophone awareness task and the homograph awareness task) and the ability to construct a new compound word by combining two known morphemes (the morpheme production task), reflecting the distinctive features of Chinese morphology. In general, MA is significantly associated with reading in Chinese (McBride-Chang et al. 2003, Shu et al. 2006, Xue et al. 2013, Pan et al. 2016), as it is across different alphabetic languages (Carlisle 2000, Lyytinen & Lyytinen 2004, Nagy et al. 2006). When lexical compounding skill is the target measure, MA is a stronger correlate of reading in Chinese than in alphabetical languages (Ruan et al. 2018). Moreover, the importance of various MA measurements to Chinese reading is modulated by grade level (Li et al. 2012). Specifically, sensitivities to homophones and homographs are essential for upper-grade children because they must distinguish between many homophones and homographs in their comparatively larger vocabulary of spoken and written Chinese. For younger children with a smaller vocabulary, lexical compounding skill plays a particularly important role because putting a word in context is the most optimal way to distinguish one meaning from another, and transfer of the lexical compounding skill from spoken language to print helps them guess at words composed of both known and unknown morphemes.

Although the underlying mechanism remains unclear, RAN—the ability to name, as quickly as possible, highly familiar stimuli such as letters, digits, colors, and objects—is a skill strongly associated with reading across languages (Parrila et al. 2004, Moll et al. 2009, Yeung et al. 2011, Liao et al. 2015). Originally considered a phonological processing skill, RAN was thought to reflect the ability to access and retrieve phonological codes from long-term memory (Wagner & Torgesen 1987). However, other researchers argued that RAN and reading are related because they share some common processes such as visual-orthographic processing (Bowers & Wolf 1993), access to lexical representations (Wolf & Katzir-Cohen 2001), arbitrary connections between symbols and sounds (Manis et al. 1999), and rapid execution of general cognitive processes (Kail et al. 1999). Given the distinct features of Chinese orthography, e.g., the complex visual-orthographic properties of Chinese characters and the lack of symbol–sound correspondence rules, some researchers ascribed particular importance to RAN in Chinese reading and predicted higher correlations between RAN and reading in Chinese than in English (Siok & Fletcher 2001, Luo et al. 2013). However, three meta-analysis studies revealed no significant differences in RAN–reading relation extents across languages (Georgiou et al. 2008, 2015; Song et al. 2016), indicating that RAN is a universal correlate of reading in languages with alphabetic and nonalphabetic orthographies.

Taken together, the above studies revealed that the four linguistic and cognitive skills useful in alphabetic languages, i.e., visual-orthographic knowledge, PA, MA, and rapid naming, are the core reading-related abilities of Chinese children but that the extent of correlation of some skills and subskills (e.g., syllable awareness is a subskill of PA) with reading depends on the specific properties of Chinese orthography, phonology, and morphology. While it is universal that readers' abilities to encode printed words, to manipulate speech sounds and word structures, and to analyze the meaning of compound words are closely associated with reading development across languages, the relative importance of these skills to Chinese reading development is influenced by age-appropriate knowledge of the distinct Chinese orthographical, phonological, and morphological features.

4. ADVANCES IN RECENT STUDIES ON CHINESE DEVELOPMENTAL DYSLEXIA

Although research on Chinese DD started much later than that on alphabetic languages, great progress has been made in the past two decades. Specifically, a large number of studies have examined linguistic profiles in association with specific aspects of orthography, phonology, and morphology (Ho et al. 2004, Shu et al. 2006, Cheung et al. 2009, Li & Ho 2011, Liao et al. 2015, Tong et al. 2019, Lin et al. 2020, Cheng et al. 2021; see Peng et al. 2017 for a meta-analysis and McBride-Chang et al. 2018 for a review). An increasing number of electrophysiological and neuroimaging studies have explored the neural mechanisms underlying Chinese DD (Siok et al. 2004, 2009; Hu et al. 2010; Chung et al. 2012; Zhang et al. 2012; Cao et al. 2017; Su et al. 2018; Feng et al. 2020; Zhang et al. 2021; see Yan et al. 2021 and Li & Bi 2022 for meta-analyses). Some genetic studies have tested the associations between susceptibility genes and dyslexia-related behavioral and neural phenotypes (Su et al. 2015, Kong et al. 2016, Sun et al. 2017, Waye et al. 2017). The results of these studies provide behavioral, neural, and genetic evidence for the language-universal and language-specific mechanisms of dyslexia.

4.1. Linguistic Profiles of Chinese Developmental Dyslexia

Even though the four linguistic skills discussed above have been widely accepted as the precursors to reading acquisition in typically developing children, specific evidence for dyslexia is still needed for both theoretical and practical considerations. Because impairment in one or more of the four skills might result in reading difficulties, the following should be clarified: (*a*) which specific skill impairments lead to reading failure; (*b*) whether impairments in different skills induce reading failure to a similar extent or whether certain deficits constitute a more serious handicap than others; and most importantly, (*c*) whether linguistic profiles of dyslexia in Chinese are language specific or similar to those of dyslexia in alphabetic orthographies. From a practical point of view, proper characterization of linguistic profiles of Chinese DD provides the basis for developing effective intervention.

In the past, researchers had assumed that Chinese characters had to be learned one by one as logograms through rote memorization (Makita 1968, Rozin et al. 1971, Kline 1977). That is, there were direct links between Chinese orthography (with each character having seemingly random and idiosyncratic composition) and semantics, and therefore the meaning of a Chinese character could be directly accessed without converting orthography to phonology during reading. However, this belief does not reflect the configural structure of Chinese characters and the actual process of Chinese reading. On the one hand, among the small number (approximately 7% of the total) of single-component Chinese characters, the meanings of a few characters can be deduced from appearance. After a long period of evolution, most single-component Chinese characters appear quite different from the original. The direct orthography-to-semantics link, therefore, is weak. For example, it is difficult to obtain the meanings water and tree from the Chinese characters 水 and 木, respectively. On the other hand, among the large number (more than 80% of the total) of pictophonetic compounds with strong regularity in character formation, phonetic radicals provide full or partial information about the pronunciations of the Chinese characters. For example, the pronunciations of 惊 (surprise) and 芳 (fragrant) can be directly derived from their phonetic radicals (京 and 方, respectively). Thus, phonology is relevant for reading in Chinese, as it is for reading in English and any other language. That is, reading in any language requires access to phonological representations of written words, although the orthography-to-phonology correspondence differs across languages (Ziegler 2006). Specifically, readers of alphabetic languages like English usually use grapheme–phoneme correspondence rules, while readers of Chinese use character–syllable correspondences.

As one of the widely known phonological processing deficits, PA deficit is the primary indicator of dyslexia in alphabetic languages (Ziegler & Goswami 2005). Studies on Chinese DD have long paid special attention to PA deficit (Ho et al. 2002, 2004), and there is a consensus that PA deficit is also a legitimate core deficit for dyslexia in Chinese at both the segmental and suprasegmental levels (Ziegler 2006, McBride-Chang et al. 2018). For example, a recent study reported that approximately 60% of Chinese dyslexic children exhibited PA deficit (Cheng et al. 2021). Furthermore, the importance of PA deficit to Chinese DD is not affected by the way children are taught to read in Hong Kong, where a direct look-and-say approach is adopted, in contrast to Mainland China, where an alphabetic-based transcription system is used in addition to Chinese scripts (Peng et al. 2017). Although it has been widely accepted that PA deficit in segmental phonemes (i.e., consonants and vowels) as an indicator of dyslexia is less important in Chinese than in alphabetic languages, researchers are debating the relative importance of deficits in various suprasegmental phonological units to Chinese dyslexia (Li & Ho 2011, Wang et al. 2012, Ho 2014, Wang et al. 2017). Some researchers emphasize the importance of syllable awareness and rime awareness deficits (Ho 2014, Yeung et al. 2014), while others highlight the phonological status of lexical tones and emphasize the role of lexical tone awareness deficit (Li & Ho 2011, Wang et al. 2017, Deng & Tong 2021). In a study that examined both rime and lexical tone awareness deficits, more than one-third of Chinese dyslexic children showed at least one aspect of lexical tone awareness deficit (e.g., tone discrimination of known words and tone production of nonwords), in contrast to the lower proportion (approximately 20%) with a rime awareness deficit (Li & Ho 2011), indicating that lexical tone awareness deficit is more important to Chinese DD than is rime awareness deficit. By contrast, Wang et al. (2012) reported a higher occurrence of rime awareness deficit than of lexical tone awareness deficit in Chinese dyslexic children. The discrepancy in the proportions of different suprasegmental phonological deficits needs to be further investigated.

In addition to the consensus on PA deficit in Chinese DD, researchers have reached an agreement that PA deficit stems from lower-level perceptual deficits, such as difficulties in categorical perception of speech sounds and auditory sensory processing. Categorical perception is a fundamental characteristic of speech perception that explains how the infinite variant spoken forms of speech sounds are mapped onto a discrete set of phonetic categories. Its core feature lies in the perceptual warping and partitioning, as demonstrated in identification and discrimination tasks, of a speech continuum comprising multistep changes from one category to another. That is, listeners are much more sensitive to small acoustic differences that cross phonemic boundaries than to the same acoustic differences that are within the same phonological category (Liberman et al. 1957). Previous studies have consistently found that dyslexic children of alphabetic languages perceive speech sounds less categorically than do typically developing children; that is, speech discrimination in dyslexic children is largely driven by their ability to detect acoustic differences irrespective of the within- or across-category phonemic status (see Noordenbos & Serniclaes 2015 for a review). Significant categorical perception deficits associated with Chinese DD have also been confirmed in previous studies on voicing contrasts of stop consonants (Cheung et al. 2009, Liu et al. 2009) and especially on pitch patterns of lexical tones (Cheung et al. 2009, Zhang et al. 2012). Specifically, dyslexic children exhibited shallower identification functions and larger identification inconsistency with stimuli from the same category than did typically developing children. Furthermore, categorical perception is significantly correlated with PA, which mediates the association between categorical perception and reading (Cheung et al. 2009). In the early years of research, some researchers argued that the deficits in PA and categorical perception underlying dyslexia are rooted in particular auditory sensory processing deficits, such as rapid auditory temporal processing deficit (Tallal 1980), amplitude envelope onset deficit (Goswami et al. 2002), and frequency modulation depth deficit (Witton et al. 2002). The existence of many lower-level auditory deficits has been confirmed in Chinese DD, in agreement with studies in alphabetic languages, and moreover, each deficit usually accounts for a significant amount of unique variance in PA or reading (Goswami et al. 2011, Tong et al. 2018, Wang 2020). The relations among various auditory processing deficits and their relations with PA and/or reading need to be clarified in future studies.

Owing to the unique nonalphabetic features of Chinese characters, difficulty in orthographic processing has been assumed to be one of the most dominant deficits underlying Chinese DD (Ho et al. 2002). Specifically, deficient knowledge of character structures and radical positions impedes and delays character recognition and thus makes reading a laborious task. Many previous studies reported impaired orthographic processing in Chinese dyslexic children (Ho et al. 2002, 2004; Chung et al. 2010; Wang et al. 2012; Lin et al. 2020), although the percentages of dyslexic children with orthographic deficits appear to vary across studies, ranging from approximately 30–50% in Ho et al. (2004) and 50–60% in Wang et al. (2012) to approximately 10% in Liu et al. (2006). A recent meta-analysis showed that, compared to chronological age–matched typically developing children and reading level–matched typically developing children, dyslexic children have more severe and milder deficits in orthographic processing, respectively (Peng et al. 2017), indicating that orthographic deficits may be a causal factor for Chinese DD. Given that there are bidirectional relations between reading and the underlying linguistic skills, the logic for such an inference is that (*a*) the poorer performance in dyslexic children relative to both of these groups of typically developing children is more likely to be a causal factor of DD and (*b*) the poorer performance in dyslexic children relative to the chronological age–matched typically developing children but not the reading level–matched typically developing children is more likely to be a consequence of DD.

Some researchers further argued that orthographic deficits in Chinese dyslexia might result from visual deficits at the lower perceptual level (Ho 2014). Since Chinese scripts (both the traditional and simplified versions) are visually complex and some Chinese characters are distinguished on the basis of subtle strokes and stroke patterns (e.g., 甲 versus 申, 士 versus 土, 戊 versus 戌 versus 戍), impairments in visual skills (such as visual form identification and differentiation), perception of visual-spatial relations, and visual memory likely contribute to Chinese reading failure. Some previous studies have shown that visual deficits distinguish children with and without dyslexia in Chinese and that a large proportion (more than 30%) of Chinese dyslexic children have visual processing impairments (Ho et al. 2002, 2004). In a recent meta-analysis study (Peng et al. 2017), visual deficits were found in Chinese DD when dyslexic children were compared to chronological age–matched children, but not when they were compared to reading level–matched children. Furthermore, visual attention span deficit was only recently suggested as an alternative underlying visual deficit of Chinese DD because there is no space to mark word boundaries in Chinese text and thus readers need to process several characters simultaneously to determine which characters constitute a word (Chen et al. 2019). Deficiency in visual attention span may impair reading by preventing readers from processing two or more Chinese characters at a time. Therefore, readers with such a deficit need more time to locate a word boundary, and reading efficiency decreases. Two recent studies confirmed visual attention span deficit in Chinese DD (Chen et al. 2019, Cheng et al. 2021). However, only one of these two studies (Chen et al. 2019) found that this visual processing deficit is an independent cause of dyslexia, and the other (Cheng et al. 2021) did not.

Another example of visual-orthographic knowledge is handwriting or copy of print. Because of the visual complexity of Chinese characters, handwriting or copying of Chinese characters is the most dominant teaching method for promoting literacy development of children in the lower grades of elementary schools. Therefore, reading and writing in Chinese are closely related. Previous studies revealed that visual contour integration skills are related to the performance of handwriting Chinese characters in primary school children (Li-Tsang et al. 2012), and copying skills of Chinese characters distinguished children with and without dyslexia (McBride-Chang et al. 2011, Kalindi et al. 2015). These findings have particularly important implications for developing intervention programs.

Given the large number of homophones and semantic transparency at both the character and word levels in Chinese, MA has been proposed as a core linguistic construct for understanding Chinese DD (Shu et al. 2006, McBride-Chang et al. 2018). Previous studies found that MA measured by tasks of homophone sensitivity and lexical compounding is successful in distinguishing children with and without dyslexia (Shu et al. 2006, Chung et al. 2010), as well as in differentiating children with family risk from those with no familial risk or language delay (McBride-Chang et al. 2008a). Furthermore, MA performance contributes to reading variances in both dyslexic and typically developing children and plays a more important role than do PA and RAN in predicting dyslexia status (Song et al. 2020). Interestingly, results from an 8-year longitudinal study showed that preliterate PA provides a basis for the development of postliterate MA, which is a significant predictor of future reading development (Pan et al. 2016). Moreover, the importance of MA is modulated by dyslexia severity, with its role more salient for children with severe dyslexia than for those with mild dyslexia (Yeung et al. 2014, Song et al. 2020). In a recent meta-analysis (Peng et al. 2017), MA deficit is observed only when dyslexic children are compared to age-matched typically developing children, but not when compared to reading level–matched children, indicating that MA deficit is likely a consequence of reading delay rather than a causal factor of dyslexia. Further investigations are needed to determine whether MA deficit is a particularly important predictor of Chinese DD when the severity of dyslexia and complex interactions among PA, MA, and reading are considered with respect to age and the developmental trajectory of reading acquisition.

Along with PA deficit, RAN deficit is the other core deficit underlying dyslexia in alphabetic languages, although researchers are still debating its nature (Ziegler et al. 2010). Studies have consistently demonstrated that Chinese dyslexic children in both Mainland China and Hong Kong are slow in RAN tasks (Shu et al. 2006, Chung et al. 2008, Liao et al. 2015, Cheng et al. 2021; see McBride-Chang et al. 2018 for a review). In particular, Ho and colleagues (Ho et al. 2002, 2004; Wong & Ho 2010) proposed that RAN is the most dominant cognitive deficit underlying Cantonese (a dialect of Chinese) dyslexia in Hong Kong because teachers have adopted a direct look-and-say teaching approach. Under this approach, children are taught by rote to learn Chinese characters, including their visual configurations and pronunciation, as a whole unit, and thus during reading, children tend to rely on the arbitrary character–sound connections more than Mandarin children, who are taught to learn Chinese characters by use of alphabetic-based transcription systems (Pinyin in Mandarin China and Zhuyin Fuhao in Taiwan). However, a recent meta-analysis did not confirm the modulation effect of location/teaching approach on the relationship between RAN and Chinese reading (Peng et al. 2017). Furthermore, previous studies are inconsistent with the modulation effect of age/grade on the relationship between RAN and

Chinese reading as well as the importance of various RAN tasks to reading (Song et al. 2016, Peng et al. 2017). All these inconsistencies in previous research, particularly the associations between deficits in various RAN tasks and Chinese reading difficulty, need to be further investigated.

Taken together, the research on Chinese DD, consistent with evidence from research on dyslexia in alphabetic languages, shows that Chinese DD results from multifactorial deficits. Generally speaking, these deficits are composed of impairments at two levels: Impairments at the linguistic level include difficulties in phonological, orthographic, and morphological processing and rapid naming, and impairments at the sensory level include dysfunctions in visual and auditory processing. Cumulative evidence suggests that at the linguistic level there are both language-universal (phonological and rapid naming) deficits and language-modulated (orthographic and morphological) deficits in Chinese DD, although researchers disagree as to the relative importance of these deficits to Chinese reading failure. The language-universal and language-modulated deficits associated with Chinese DD are further supported by studies on Chinese-English bilingual children (Ho & Fong 2005, Chung & Ho 2010, Tong & McBride 2017, Chung & Lam 2020, Huo et al. 2022). All these studies have consistently showed that native (L1) Chinese dyslexic children encountered difficulties in learning to read English as a second language (L2), indicating the cooccurrence of L1 and L2 reading difficulties and shared underlying mechanisms. Furthermore, PA and RAN deficits in L1 transferred to L2, while orthographic deficits in L1 caused the least impairment in English reading (Ho & Fong 2005, Huo et al. 2022). At sensory levels, however, researchers are hotly debating the nature of various auditory and visual processing deficits and their intrinsic relations with linguistic deficits and reading difficulties. These unclarified issues at the linguistic and sensory levels need to be addressed in future investigations.

4.2. Brain Abnormalities in Chinese Developmental Dyslexia

Research on the neural mechanisms for DD started in the 1970s. Early studies are usually based on histological brain examinations. For example, reduced left–right asymmetry of the planum temporale was reported in an adult dyslexic on the basis of a postmortem brain examination by Galaburda & Kemper (1979). Currently, noninvasive neuroimaging techniques such as positron emission tomography, event-related potential (ERP), and magnetic resonance imaging (MRI) are widely used by researchers around the world to examine brain dysfunction in dyslexia.

The first functional MRI study on Chinese dyslexia (Siok et al. 2004) reported reduced activation in the middle frontal gyrus (MFG) during both homophone judgment and character decision tasks in dyslexic children relative to typically developing children. The functional abnormality of the MFG in Chinese DD was further supported by a subsequent functional and structural MRI study of Siok et al. (2008); this study showed reduced gray matter volume in the same brain region and significant correlation between gray matter volume and activation in a character rime judgment task (Siok et al. 2008). Siok et al. (2004, 2008) argued that the functional and structural abnormalities in the left MFG reflect Chinese-specific rather than language-universal pathophysiology of dyslexia and that this pathophysiology is dependent on the distinctive correspondence between Chinese characters (orthography), syllables (phonology), and morphemes (morphology). Specifically, during fluent Chinese reading, the MFG is responsible for the direct mapping of visual characters to the corresponding monosyllabic sounds and morphemes in the absence of grapheme-to-phoneme processes. Decreased activation and gray matter volume in the left MFG in dyslexic children impair its ability to be a main hub for the coordination and integration of information about written characters in visual and verbal working memory and thus lead to reading failure.

The importance of left MFG dysfunction to Chinese DD has been confirmed by other functional MRI studies, but it is assumed to have more roles than originally suggested by Siok and colleagues (Siok et al. 2004, 2008). For example, Cao et al. (2017) found that, during an auditory rime task, Chinese dyslexic children exhibit reduced activation in the left MFG relative to typically developing children, indicating that underactivation of the left MFG is associated with auditory phonological processing deficits in Chinese DD. Zhou et al. (2015) demonstrated that the strengths of resting-state functional connectivity between the left MFG and the intraparietal sulcus/visual word form area differ between dyslexic and typically developing children and that furthermore functional connectivity, which requires more visual attention processing, is significantly correlated with scores of reading fluency, but not with scores of character decision (Zhou et al. 2015). In a recent meta-analysis study, the left MFG showed common hypoactivation across dyslexic children in Chinese and alphabetic languages and at the same time stronger hypoactivation in Chinese dyslexics compared with alphabetic language dyslexics, indicating both a language-universal phonological processing deficit and a language-modulated visual-orthographic deficit in Chinese dyslexia (Li & Bi 2022). Given the diverse functions of the MFG in language processing (e.g., lexical semantics, phonological processing and category selection, orthography-to-phonology conversion), the exact roles of the MFG in normal and impaired reading should be investigated to further determine whether the MFG activation patterns associated with dyslexia reflect Chinese-specific or language-universal properties.

The neural correlates of other linguistic profiles of Chinese DD have also been investigated. Orthographic deficits are reflected by a lack of amplitude difference in the N400 ERP component between pseudocharacters and noncharacters (Chung et al. 2012) and by decreased activation in the visual word form area during Chinese character recognition (Siok et al. 2004, Feng et al. 2020), indicating a language-universal deficit at the neural level, namely that dyslexic children are weak in using orthographic knowledge to distinguish between legal and illegal characters. At the same time, increased activation in the right inferior occipital and middle temporal regions indicates a language-specific compensatory strategy for visual-spatial analysis of Chinese characters (Siok et al. 2004, 2009; Liu et al. 2012; Li & Bi 2022). Phonological deficits are reflected by a lack of amplitude difference in the mismatch negativity (MMN) ERP component between within-category and across-category lexical tonal contrasts (Zhang et al. 2012) and by decreased activation in the left superior temporal and inferior frontal regions during rime judgment (Liu et al. 2012, Cao et al. 2017, Li & Bi 2022), indicating a language-universal phonological deficit at the neural level. Morphological deficits are reflected by a smaller incongruency effect in the left dorsal posterior and ventral anterior inferior frontal gyrus during semantic relatedness judgment, indicating a language-specific deficit, namely that the dyslexic children are less sensitive to morphological information (Liu et al. 2013).

Taken together, neuroimaging studies have provided some neural evidence for language-universal and language-specific linguistic deficits in Chinese DD. Due to sample size limitations, these findings need to be verified in future studies, especially given the widespread concerns about the unreliability inherent in small-scale neuroimaging studies. Compared with the great number of neuroimaging studies on dyslexia in alphabetic languages and behavioral studies on dyslexia in Chinese, there are a very limited number of neuroimaging studies on dyslexia in Chinese. In particular, possible structural disruptions in specific brain areas and in the white matter connecting these areas that are associated with various linguistic deficits have not been systematically investigated. More neuroimaging studies on Chinese DD that adopt different types of sequences (e.g., T1 and diffusion) and data analysis methods (e.g., multivariate analysis, fractional anisotropy and tractography, and voxel-based and surface-based morphometry) and that have larger sample sizes need to be conducted using various tasks for characterizing the complete neurobehavioral profile of Chinese DD.

4.3. Susceptibility Candidate Genes for Chinese Developmental Dyslexia

Clinical observations suggest that, as in many other linguistic and communicative disorders, familial history is an important factor of dyslexia. In alphabetic languages, abundant family research over more than three decades has provided convincing evidence that dyslexia is a highly heritable disorder, with a heritability of 40–60% (Fisher & DeFries 2002). The first series of susceptibility candidate genes for dyslexia reported between 2003 and 2006 include *DYX1C1*, *ROBO1*, *KIAA0319*, and *DCDC2* (Galaburda et al. 2006). Since then, additional candidate genes such as *GCFC2* and *MRPL19* have been proposed (Anthoni et al. 2007). The identified susceptibility genes are associated not only with the diagnosis of dyslexia but also with variations in reading ability within the general population. Furthermore, many of the reading-related linguistic (e.g., phonological processing) and basic perceptual (e.g., rapid auditory temporal processing) phenotypes seem to be influenced by dyslexia candidate genes (Marino et al. 2007, Centanni et al. 2014). At the neural level, dyslexia susceptibility candidate genes are associated with electrophysiological responses (e.g., the auditory ERP component, MMN), functional activation, and anatomical variations (Czamara et al. 2011, Cope et al. 2012, Skeide et al. 2016).

Genetic studies on Chinese DD are comparatively sparse, with efforts mainly aimed at verifying findings from alphabetic languages in Chinese. Such efforts are important given that Chinese is linguistically distinctive in orthography, phonology, and morphology. In accordance with studies on dyslexia in alphabetic languages, the *DRD2* (Chen et al. 2014), *DCDC2* and *KIAA0319* (Sun et al. 2014), and *DIP2A* (Kong et al. 2016) genes are associated with dyslexia in Chinese. By contrast, Waye et al. (2017) found that *DCDC2* is not strongly associated with dyslexia in Hong Kong Chinese children, and Shao et al. (2016) reported in a meta-analysis that none of the six investigated markers in or near the *KIAA0319* gene are associated with DD. At the neural level, Su et al.'s (2015) longitudinal study found a significant interaction in Chinese 12-year-old children's N170 responses between the single-nucleotide polymorphism *rs1091047* in the *DCDC2* gene and home literacy at 3 years old, as measured by the number of books read to them at home, reflecting gene–environment interaction in early literacy development that has a subsequent impact on the neural correlates of orthographic processing in Chinese children with variations in reading ability. Sun et al. (2017) found that the polymorphisms *rs4535189* and *rs6803202* in the *ROBO1* gene regulate word list reading performance by modulating the fiber microstructures of the genu of the corpus callosum, providing insight into the functions of *ROBO1* and the gene-to-brain mechanisms underlying reading. As both Su et al. (2015) and Sun et al. (2017) recruited children with a wide range of reading abilities, whether their findings apply to dyslexia needs to be further investigated.

Only a small number of genes have so far been implicated in DD, with a notable portion of heritability still unexplained. More genetic studies in different languages, including Chinese, are warranted to identify new susceptibility genes (some of which might be language specific) and to clarify the relations among the linguistic profiles, neural mechanisms, and genetic bases underlying dyslexia.

4.4. Intervention Studies on Chinese Developmental Dyslexia

Evidence-based intervention provides opportunities to test theoretical models and bridge the gap between research and practice. In Chinese DD, studies aiming to ameliorate reading difficulties through proper interventions started almost at the same time as the basic research studies. Considerable progress has been made in the past 20 years. Various approaches have been put forward on the basis of different theoretical and empirical considerations. These approaches focus on single or comprehensive linguistic or nonlinguistic skills and help dyslexic children to improve their reading ability. Because various phonological training methods constitute an important part of intervention programs for dyslexia in alphabetic languages (Schneider et al. 2000), PA instructions have also been developed in intervention studies on Chinese DD (Zhou et al. 2012, Wang 2017). Results show that PA training significantly improves dyslexic children's PA, but the effect on reading is not very strong. For example, Wang (2017) found that dyslexic children who were trained on onset and rime awareness make greater improvements in onset awareness (35.9%) and rime awareness (41.3%) than in Chinese character reading (2.7%; marginally significant, with $p = 0.06$). Further examinations of the dyslexic participants by dividing them into different age groups revealed that PA training significantly improved reading in children under 10 years (6.6%, $p < 0.01$), but not in children above 10 years, indicating a clear age effect of the impact of PA training on Chinese character reading. Given the lack of direct grapheme-to-phoneme correspondence in Chinese and the prominent roles of syllables and lexical tones, various PA intervention programs that focus on syllable and lexical tone awareness may be more beneficial and need to be examined in future investigations. Because of the logographic aspect of Chinese script and the important role of orthographic deficits in Chinese DD, orthographic skill training has long been adopted in intervention studies. For example, dyslexic children who were trained on the structure knowledge of Chinese characters outperformed controls in Chinese character and word reading (Ho & Ma 1999). A number of studies have consistently shown that systematic training on Chinese character structures has unambiguously positive effects on reading acquisition of Chinese children with or without dyslexia (Packard et al. 2006, Wu et al. 2009, Wang et al. 2021). A recent study also tested intervention on MA (the role of each character as a lexical morpheme in a compound word) (Wang et al. 2021). Given that studies on kindergartners demonstrated that MA training promotes early literacy (Zhou et al. 2012, Wang & McBride 2017), this approach is promising for children at risk for dyslexia. Moreover, some researchers have focused on reading fluency training on the basis of the RAN deficit in Chinese DD. Specifically, the reading acceleration paradigm is effective in helping dyslexic children to improve reading fluency and at the same time maintain superior comprehension levels (Dai et al. 2016).

Especially noteworthy is a recent study that developed a comprehensive intervention combining transcranial direct current stimulation and behavioral training and evaluated the intervention effect with functional MRI (Zhang et al. 2021). Specifically, the intervention targeted orthographic awareness and reading fluency, and functional MRI was deployed before and after the intervention. Results showed that the combination of etymological literacy teaching and transcranial direct current stimulation not only improved orthographic awareness and reading fluency but also enhanced the activation levels of critical brain regions associated with reading in Chinese dyslexic children. The comprehensive intervention and assessment approach provides a foundation and guidance for testing neuroanatomical models of dyslexia in general and future practice and evaluation for Chinese DD.

Different from interventions that focus on reading-related linguistic skills, various interventions aimed at foundational auditory and visual sensory skills, including visual perceptual training (Meng et al. 2014), visual attention span training (J. Zhao et al. 2019), and auditory temporal perceptual training (Zhang et al. 2018), have also been developed. In addition, some researchers emphasize the importance of working memory training (Yang et al. 2017). Sensory- and memory-based interventions improve reading ability by improving some executive functions such as cognitive operation, inhibitory control, and memory.

Taken together, various linguistic and nonlinguistic interventions have proven to be helpful in the remediation of Chinese DD. However, the beneficial effects of various interventions differ greatly and may be modulated by the heterogeneity inherent in dyslexia. Given that dyslexia is a multifactorial disorder and that there are large individual variations in the underlying deficits, there need to be coordinated systematic efforts to build large databases of dyslexic cases with longitudinal measures to understand such heterogeneity and to refine individualized assessment and intervention.

5. LIMITATIONS IN PREVIOUS STUDIES AND FUTURE DIRECTIONS

The past two decades have witnessed a surge of interest in Chinese DD, with the early studies conducted in Hong Kong and studies in Mainland China beginning in the past decade. Although significant advances have been made in understanding Chinese DD, there are limitations at both the theoretical and practical levels, and much work remains to be done.

First, previous studies differ to some extent in the criteria for diagnosing dyslexic children, although Chinese DD is diagnosed similarly as in alphabetic languages. This heterogeneity of diagnosis criteria is due to the lack of a standardized screening and assessment tool for Chinese DD. Chinese DD is diagnosed on the basis of Chinese character and word reading accuracy in some studies, but on the basis of character and word reading accuracy/fluency in other studies. A number of studies also measure sentence reading accuracy/fluency and writing skills. Furthermore, the cutoff criteria vary from study to study, with at least three different options adopted (i.e., −1, −1.25, and −1.5 standard deviations below the average level of age-matched typically developing children). It is time for researchers to develop standardized materials and criteria for diagnosing Chinese DD. For this purpose, untimed Chinese character recognition should be adopted as the primary diagnosis task, given that reading accuracy deficit is the predominant symptom of dyslexia in deep orthographies such as English and Chinese. We also suggest that a −1.5 standard deviation cutoff limit should be adopted to establish "diagnostic certainty" of Chinese DD in future studies, in accordance with the fifth edition of the *Diagnostic and Statistical Manual of Mental Disorders* (APA 2013).

Second, previous studies are often biased in behavioral measurements and subject selection. Specifically, most previous behavioral studies measure meta-linguistic skills (i.e., PA, orthographic awareness, and MA) of dyslexic children of grades 4–5 while leaving unexplored the relationships among different levels of processing (e.g., phonological processing at the highest level, categorical perception of speech sounds at the intermediate level, and auditory sensory processing at the lowest level) with respect to the developmental trajectories of reading. In particular, few studies have examined the early indicators of dyslexia in preschoolers, with very little scientific evidence to guide early diagnosis and intervention. In addition, dyslexic adults have rarely been included in previous studies on Chinese DD, which creates a great gap of our knowledge base. In this regard, we call for more longitudinal studies to map out various levels of processing at different developmental stages. In particular, behavioral and neural measures of lower-level auditory and visual processing and speech perception, especially categorical perception in infants, toddlers, and preschoolers, can be obtained for the purpose of developing early clinical markers of Chinese DD. Longitudinal studies would also help clarify the ongoing debate over the nature (i.e., whether reading development is delayed or deviant) of dyslexia.

Third, there has been a lack of collaboration among researchers in the fields of linguistics, psychology, neuroscience, genetics, and education. While linguists and psychologists have developed various tasks to explore the linguistic deficits underlying Chinese DD, only a limited number of tasks have been used in neuroimaging and genetic studies. Interpretations based on the results of only one or two tasks may be biased; e.g., researchers are fiercely debating the functions of MFG in normal and impaired Chinese reading. In addition, dyslexia has attracted little attention in the field of education in Mainland China, and because teachers and parents lack knowledge about dyslexia, they cannot provide useful and effective help. Future studies should strengthen collaboration among linguists, psychologists, neuroscientists, and geneticists to better understand the language-universal and language-specific neurobiological mechanisms underlying Chinese

DD. Furthermore, dyslexia research should not be purely academic. Future studies should also explore how to improve public awareness about dyslexia and how to solicit social support for dyslexic children and their families.

Fourth, comorbidity between dyslexia and other neurodevelopmental disorders is not well controlled in previous studies of Chinese DD. Studies of alphabetic languages have found that dyslexia cooccurs in approximately 20–60% of individuals with other neurodevelopmental disorders such as attention deficit/hyperactivity disorder, autism spectrum disorder, specific language impairment, and math disability. Yet most previous studies on Chinese DD recruit children meeting the criteria for dyslexia without screening for other coexisting disorders. Comorbidity of dyslexia with other disorders should be properly addressed in future studies. On the one hand, studies on Chinese DD should recruit dyslexic individuals through scrutinized screening. On the other hand, behavioral, neural, and genetic studies on the comorbidity of dyslexia with other language and even music disorders (e.g., specific language impairment and amusia) will contribute to the ongoing debate over whether various deficits can be treated as different forms of a common underlying cognitive learning disorder.

6. CONCLUSION

Chinese is uniquely positioned as a logographic language, with its distinct orthography, phonology, and morphology. By examining measures of orthographic, phonological, and morphological processing in connection with literacy skills, studies on Chinese DD provide important insight into the language-universal and language-specific mechanisms underlying normal reading and reading disorders. This review draws together evidence from behavioral, neural, and genetic studies on Chinese DD in the past two decades. The data collectively indicate shared phonological and RAN deficits in linguistic profiles of dyslexia, while orthographic and morphological deficits are modulated to some degree by the linguistic properties of Chinese. A unified linguistic theory for the neurobiology of dyslexia needs to take into account how sensory and motor deficits (i.e., rapid auditory processing and visual perception) are associated with subtypes of dyslexic symptoms and how different neurobehavioral developmental disorders overlap with dyslexia. Future lines of work should address whether there exist language-universal and language-specific auditory and visual processing deficits and whether there exist correspondences among the deficit in a specific reading-related skill, the dysfunction of specific brain regions, and variations of specific genes.

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