Impaired processing of spatiotemporal visual attention engagement deficits in Chinese children with developmental dyslexia

Baojun Duan
School of Teacher Education,
Hexi University, Zhangye, China

Xiaoling Tang
School of Teacher Education,
Hexi University, Zhangye, China

Datao Wang
School of Teacher Education,
Hexi University, Zhangye, China

Yanjun Zhang
School of Teacher Education,
Hexi University, Zhangye, China

Guihua An
School of Teacher Education,
Hexi University, Zhangye, China

Huan Wang
School of Teacher Education,
Hexi University, Zhangye, China

Aibao Zhou
School of Psychology,
Northwest Normal University, Lanzhou, China
Key Laboratory of Behavioral and Mental Health
of Gansu Province, Lanzhou, China

Emerging evidence suggests that visuospatial attention plays an important role in reading among Chinese children with dyslexia. Additionally, numerous studies have shown that Chinese children with dyslexia have deficits in their visuospatial attention orienting; however, the visual attention engagement deficits in Chinese children with dyslexia remain unclear. Therefore, we used a visual attention masking (AM) paradigm to characterize the spatiotemporal distribution of visual attention engagement in Chinese children with dyslexia. AM refers to impaired identification of the first (S1) of two rapidly sequentially presented mask objects. In the present study, S1 was always centrally displayed, whereas the spatial position of S2 (left, middle, or right) and the S1–S2 interval were manipulated. The results revealed a specific temporal deficit of visual attentional masking in Chinese children with dyslexia. The mean accuracy rate for developmental dyslexia (DD) in the middle spatial position was significantly lower than that in the left spatial position at a stimulus onset asynchrony (SOA) of 140 ms, compared with chronological age (CA). Moreover, we further observed spatial deficits of visual attentional masking in the three different spatial positions. Specifically, in the middle spatial position, the AM effect of DD was significantly larger for the 140-ms SOA than for the 250-ms and 600-ms SOA compared with CA. Our results suggest that Chinese children with dyslexia are significantly impaired in visual attentional engagement and that spatiotemporal visual attentional engagement may play a special role in Chinese reading.

Introduction

Developmental dyslexia (DD), which is characterized by difficulties with accurate or fluent word recognition and spelling despite adequate instruction intelligence and sensory abilities, is considered the most common neurodevelopmental disorder (Gori & Facoetti, 2015;

Citation: Duan, B., Tang, X., Wang, D., Zhang, Y., An, G., Wang, H., & Zhou, A. (2024). Impaired processing of spatiotemporal visual attention engagement deficits in Chinese children with developmental dyslexia. *Journal of Vision*, *24*(13):2, 1–12, https://doi.org/10.1167/jov.24.13.2.

https://doi.org/10.1167/jov.24.13.2 Received January 24, 2024; published December 3, 2024 ISSN 1534-7362 Copyright 2024 The Authors

Lyon, Shaywitz, & Shaywitz, 2003; Shaywitz & Shaywitz, 2005). In recent years, a large number of studies have suggested that a visuospatial attention deficit may be a more basic cognitive factor leading to dyslexia (Brannan & Williams, 1987; Facoetti, Paganoni, Turatto, Marzola, & Mascetti, 2000; Fu, Zhao, Ding, & Wang, 2019; Krause, 2015; Vidyasagar & Pammer, 2010). As compared to alphabetic writing systems, numerous studies have indicated impairment of visuospatial attention for reading among Chinese children with dyslexia (Ding et al., 2016; Liu, Liu, Pan, & Xu, 2018; Liu, Xu, & Liu, 2023; McBride-Chang, Chow, Zhong, Burgess, & Hayward, 2005). However, the visual engagement deficit in Chinese children with dyslexia remains unclear. Therefore, this study aimed to verify whether there is a deficit in the spatiotemporal distribution of attentional engagement in Chinese children with dyslexia.

Numerous studies have shown that visual attentional shifting deficits have been repeatedly described in DD (Facoetti et al., 2000; Hari, Renvall, & Tanskanen, 2001; Vidyasagar & Pammer, 2010). It has also been shown that attentional shifting improves perception in several visual tasks by intensifying the signal and enhancing spatial resolution, as well as diminishing the noise effect outside the focus of attention (Boyer & Ro, 2007; Carrasco, Williams, & Yeshurum, 2002; Dosher & Lu, 2000). Therefore, attentional shifting can be considered to be the result of a processing resource engagement mechanism on the relevant object and a subsequent disengagement mechanism from the processing object to the next one. Additionally, children with DD are specifically impaired with regard to rapid engagement of their attention, indicating that both abnormal temporal attention (Ruffino et al., 2010) and spatial attention are probably supported by common attentional mechanisms (Enns & Di Lollo, 2000). Spatiotemporal visual attentional shifting has a significant impact on Chinese reading.

In comparison with alphabetic orthographies, visuospatial attention shifting may be particularly important for reading among Chinese children (Li & Bi, 2022; Liu, Chen, & Chung, 2015; Liu, Chen, & Wang, 2016; McBride-Chang et al., 2011). The basic units of Chinese characters are comprised of multiple strokes, radicals, components, and structures situated within a two-dimensional space (Yeh & Li, 2002), such that reading these Chinese characters is a highly complex process. Moreover, individual words in Chinese are comprised of one or more characters, with approximately 70% consisting of two characters, 20% consisting of a single character, and the remainder consisting of three or four characters (Yu, Zhang, Priest, Reichle, & Sheridan, 2018). The process of reading Chinese involves both accurate and rapid visual engagement and subsequent disengagement of attention on each character and requires that children identify and predict word-initial segments and spatiotemporal shifts of visual attention. This inefficient spatiotemporal distribution of attention engagement might selectively impair the word-initial segments and character decoding. Therefore, visual attention engagement might play an important role in the mechanism of the visual import of word segmentation in the reading of logographic writing systems. However, the primary interest in the present study was to examine spatiotemporal shifts of visual attention in Chinese children with dyslexia.

An increasing number of studies have indicated that children with dyslexia exhibit dysfunction in the processing of visuospatial attention (Facoetti, Lorusso, Cattaneo, Galli, & Molteni, 2005; Facoetti et al., 2000; Facoetti et al., 2003b; Facoetti, Lorusso, Paganoni, Umiltà, & Mascetti, 2003c; Franceschini et al., 2022; Ruffino, Gori, Boccardi, Molteni, & Facoetti, 2014), suggesting that children with dyslexia have a specific disability in the disengagement of visuospatial attention. Moreover, evidence from longitudinal studies and training intervention has further confirmed the causal relationship between visuospatial attention deficits and reading acquisition (Bertoni et al., 2021; Franceschini, Gori, Ruffino, Pedrolli, & Facoetti, 2012; Franceschini et al., 2013). This attentional impairment may be a consequence of general magnocellular deficits (Stein & Walsh, 1997; Vidyasagar, & Pammer, 2010). Recently, Bertoni, Franceschini, Campana, and Facoetti (2023) showed a direct neural connectivity between the posterior parietal cortex, controlling visuospatial attention, and the ventral stream for visual word recognition. Additionally, subsequent studies have also found deficits in attention engagement in children with dyslexia. For example, a number of behavioral studies have used attentional masking (AM) and attentional blink (AB) to examine the visual engagement and disengagement of non–spatial attention, revealing a specific temporal deficit of AM and AB in children with dyslexia. This attentional engagement deficit might also be a contributing factor in children's language impairments (Dispaldr et al., 2013; Facoetti, Ruffino, Peru, Paganoni, & Chelazzi, 2008). Further research using the same paradigms to examine the spatiotemporal distribution of attentional engagement in children with dyslexia showed greater AM at the shortest S1–S2 interval (where S1 is a rapidly presented, centrally displayed mask object and S2 is a rapidly presented mask object displayed left, middle, or right) and a sluggish AM recovery at the longest S1–S2 interval, as well as an abnormal lateral AM (Ruffino et al., 2010). Recently, Bertoni et al. (2024) indicated that multisensory attentional training positively affects how phonemic awareness develops in pre-readers at risk for DD. In the above studies, the result clearly suggests sluggish disengagement and engagement of visuospatial and visuotemporal attention in children with alphabetic dyslexia.

Similar to reading in alphabetic writing systems, emerging evidence supports an association between visuospatial attention and reading in Chinese children with dyslexia (Liu & Liu, 2020; Liu et al., 2016; Liu et al., 2018; Liu et al., 2023). Several behavioral studies have adopted the cue–target paradigm and indicated that Chinese individuals with dyslexia exhibit inhibition of return (IOR) in overt but not covert attentional tasks (Ding et al., 2016; Fu et al., 2019). Additionally, Chinese individuals with dyslexia exhibited no cuing effect in cue–target tasks when the stimulus onset synchronies (SOAs) were set to 100 ms. Also, compared with the children's chronological age (CA), the DD group presented an impaired facilitation effect similar to the same reading level (RL) group controls when the SOAs were 100 and 350 ms, suggesting that the impaired facilitation effect in Chinese children with dyslexia is due to development delay (Duan, Wang, Li, Ma, & Zhou, 2023). More recently, some researchers have found that poor readers show impairment in the endogenous orienting of visuospatial attention, and Chinese reading is associated with goal-directed but not stimulus-driven visuospatial attention (Liu et al., 2018). An event-related potential study reported that Chinese children with dyslexia showed a low amplitude and long latency of P1 in the high temporal frequency and low spatial frequency conditions compared with age-matched children, suggesting that Chinese children with dyslexia have difficulties with both temporal and spatial processing in the M pathway (Meng, Liu, & Bi, 2022). In a functional magnetic resonance imaging (fMRI) study, Liu, Qian, and Bi (2022) investigated the brain activation of Chinese children with dyslexia and their CA when they observed coherent motion stimuli. They found that the children were deficient in activation of the left V5/MT, and the activity of the magnocellular–dorsal pathway was closely related to orthographic awareness in Chinese students (Liu et al., 2022). However, such studies have not examined the attentional engagement deficits in visual attentional orienting in Chinese children with dyslexia. Additionally, it has been reported that children with dyslexia are impaired in the detection of brief visual signals rapidly followed by noise (Di Lollo, Hanson, & McIntyre, 1983; Visser, Boden, & Giaschi, 2004). Both temporal and spatial visual attention processing windows in which noise interferes with the signal, appear to be broader in children with dyslexia (Facoetti et al., 2008; Ruffino et al., 2010). Subsequent studies have indicated that the noise exclusion hypothesis is relevant to Chinese children with dyslexia (Ji & Bi, 2020). Therefore, it is necessary to investigate the temporal and spatial attention processing abilities of Chinese children with dyslexia using the same paradigm.

The present study aimed to investigate visual attentional engagement deficits in Chinese children with and without dyslexia. To this end, we adopted an AM task in which a target that requires a detection response to be completed before identifying the first of two sequentially presented masked objects (S1 and S2). In the experiment, S1 was always centrally displayed, whereas the locations of the S2 and the S1–S2 intervals were manipulated. Regarding the spatiotemporal distribution of visual attentional engagement, we hypothesized that there would be differences in the visual attention masking effects between DD and CA at different SOAs and spatial positions in Chinese children with dyslexia.

Methods

Participants

A total of 22 children were recruited from among 332 fourth-grade students in a local elementary school. To screen the children for dyslexia, we employed the Raven's Standard Progressive Matrices (Raven, Raven, & Court, 1998) with local norms established by Zhang and Wang (1985) and the Character Recognition Measure and Assessment Scale for Primary School Children, which has been widely used for screening Mandarin-speaking Chinese children for dyslexia (Ding et al., 2016; Meng et al., 2022; Shu, McBride-Chang, Wu, & Liu, 2006; Yang, Cai, Liu, & Liu, 2023). The screening for DD in Chinese children included the following criteria: (1) children with dyslexia demonstrated reading achievement scores of at least 1.5 years below their corresponding age; (2) children with dyslexia had normal intelligence performance; and (3) children with dyslexia had reading scores below the 25th percentile of all children in the same class, as assessed by school-based Chinese language examinations (Liu & Liu, 2020; Liu et al., 2018; Meng et al., 2022). A total of 11 Chinese children with DD and 11 normally developing children of the same CA were included in the final sample. All participants were native Chinese speakers with normal or corrected-to-normal vision. None of the participants had attention-deficit/hyperactivity disorder. Our study was approved by the local ethics committee of Northwest Normal University, and written informed consent was obtained from the parents or teachers of each participant prior to the child's participation in the study.

An analysis revealed that the two groups differed significantly in their Chinese character recognition measures, $t(20) = 16.52$, $p < 0.05$, Cohen's $d = 7.04$, as that the DD group scored significantly lower than the CA group. However, there was no significant difference

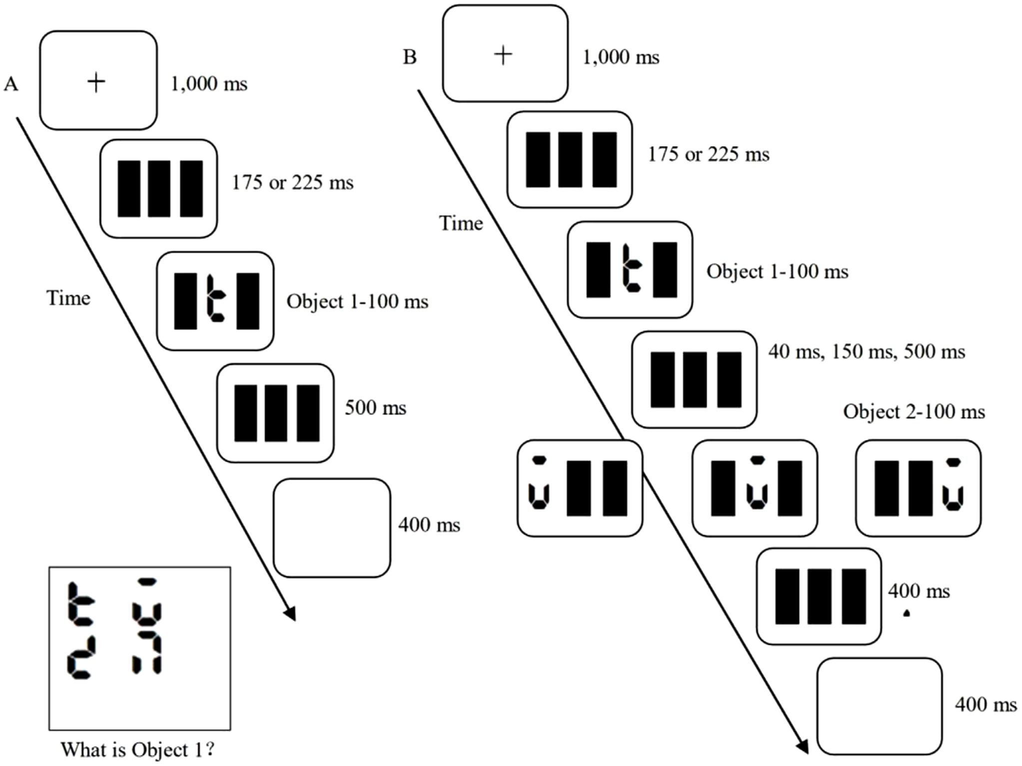

Figure 1. Schematic representation of the display used in the spatiotemporal distribution of visual attentional engagement (Dispaldro et al., 2013). (**A**) Schematic description of a trial that measured visual attention engagement in a single-task condition. Each trial started with a fixation point. The mask was presented for variable and randomized time intervals (175 ms or 225 ms) followed by the target (duration, 100 ms) and post-mask (duration, 500 ms), which were then replaced by a blank screen (duration, 400 ms). Subjects were instructed to identify the object stimuli displayed on the screen. (**B**) Schematic description of a trial for measuring the visual attention engagement in a dual-task condition. Each trial started with onset of the fixation point, followed by a variable and randomized time interval mask. S1 was presented at the central location and replaced by the post-mask. Then, S2 was displayed for 100 ms after a variable time interval, followed by the post-mask displayed for 500 ms. Subjects were instructed to identify the object S1 by choosing among the four possible object stimuli.

in performance on the age and non-verbal intelligence test, $t(20) = -0.132$, $p > 0.05$, Cohen's $d = 0.06$; $t(20) = 1.71$, $p > 0.05$, Cohen's $d = 0.73$, indicating that there were no differences in the age and non-verbal intelligence test between the DD and CA groups.

Apparatus and stimuli

This study adopted the AM task (Dispaldro et al., 2013; Facoetti et al., 2008; Ruffino et al., 2010) to examine visual attention engagement. The fixation mark was a cross presented at the center of the screen (1° visual angle). Three black rectangular blocks (1.6° × 2.7°), which served as a pre-mask, were first displayed centrally and laterally to the fixation mark (a distance of 1° visual angle). Two successive non-verbal objects (S1 and S2) were obtained by removing three line segments from a figure-eight shape (1.6° × 2.7°) comprised of seven line segments, each followed by a post-mark. Four objects were used (Dispaldro et al., 2013). Participants viewed the sequence of stimuli binocularly. E-Prime 2.0 software was used to present the stimuli (displayed on a 17-inch monitor, 1024 × 768 at 60 Hz) and record the responses.

Procedures

The experiment was conducted in a quiet room, and the experimental tasks were completed independently. All experimental stimuli were presented 40 cm from the computer screen on a gray background. Participants were instructed to keep their eyes on the fixation mark throughout the entire duration of the trial.

In order to control the visual perception of a single object (S1) in the single task condition, the mask was presented at variable and randomized time intervals (175 ms and 225 ms), followed by the target (duration, 100 ms) and the post-mask (duration, 500 ms), and was replaced by a blank (duration, 400 ms). Participants had to identify the object and choose from among four possible object stimuli displayed on the screen. They were instructed to respond as accurately as possible to the onset of the object by pressing a spacebar on a computer keyboard. No feedback was provided. The experimental session consisted of 16 trials (four trials for each figure-eight). Participants underwent eight practice trials followed by formal experiments (Figure 1A).

To measure the time course of temporal attention, we recorded the children's accuracy in identifying the first object of two sequentially masked objects. In the dual-task condition, each trial began with the onset of the fixation point. After 1000 ms, the mask was presented for a variable and randomized time interval (175 ms or 225 ms) to maintain the participants' alertness. S1 was presented for a duration of 100 ms at the central location and was replaced by a post-mask. S2 was then displayed for 100 ms after a variable time interval (i.e., 40, 150, or 500 ms) and was immediately replaced by the post-mask displayed for 500 ms. S1 and S2 were randomly selected (with replacements) from among the four possible symbols. At the end of the trial, participants were required to identify the object (S1) by choosing among the four possible object stimuli displayed on the screen. These four objects then appeared on the screen immediately after the blank (duration, 400 ms). AM refers to an impaired identification of the first (S1) of two sequentially presented mask objects. In order to conveniently record the mean accuracy rate of the first objects for participants, each participant was instructed to use the spacebar on a computer keyboard at all times and to identify the object as accurately as possible at its onset. No feedback was provided. The experimental session consisted of 63 trials divided into three blocks of 21 trials each, including seven middle-, seven left-, and seven right-location trials. Participants underwent 12 practice trials followed by the formal experiments (Figure 1B).

Results

Outliers were excluded from the datasets before analyses were carried out. In the present experiment, the mean response times of four subjects were regarded as outliers because they did not complete all experimental tasks carefully according to the instruction. This study examined the ability to recognize a figure-eight shape under single-task conditions for the DD and CA groups using a single task as the baseline condition. The mean accuracy rate of SI identification under the single-task condition was computed using an independent-sample *t*-test. The results showed that the differences were statistically significant for the DD and CA groups; the accuracy rate of the DD group was significantly lower than that of the CA group, $t(16) = -2.27$, $p < 0.05$, Cohen's $d = 1.02$. This was due to differences in the mean accuracy rates of SI identification between the DD and CA groups under the single-task condition. Based on prior research (Dispaldro et al., 2013), to obtain a general index of the attentional engagement deficit and to control for any effects attributed to perceptual masking, the S2I (S2I refers to the masked effect was removed by subtracting the AM effect from the accuracy scores in the single-task condition) was calculated under the dual-task condition. Table 1 presents the group differences in the single- and dual-task conditions.

We adopted a repeated-measures analysis of variance (ANOVA) on the mean accuracy rate of S2I with SOAs (140 and 250 ms vs. 600 ms) and spatial position (left, middle, or right) as within-subject variables and group (DD vs. CA) as a between-subject variable. The results showed that the SOA main effect was significant, $F(1, 32) = 5.05$, $p < 0.05$, $\eta^2 = 0.24$; that is, the mean accuracy rate for 140 ms was significantly lower than that for 250 ms and 600 ms. The main effect of spatial position was significant, $F(1, 32) = 7.94$, $p < 0.05$, $\eta^2 = 0.33$, and the mean accuracy rate in the middle position was significantly smaller than in the left position, but there was no significant difference between the middle and right positions. In addition, the group main effect was not significant, $F(1, 16) = 0.55$, $p > 0.05$, $\eta^2 = 0.03$. More importantly, the interaction between SOA and spatial position was significant, $F(4, 64) = 2.87$, $p < 0.05$, $\eta^2 = 0.15$, indicating a significant difference in spatial position for the SOA of 140 ms, $F(2, 34) = 7.32$, $p < 0.05$, but there was no significant difference in spatial position for the SOAs of 250 ms or 600 ms ($p > 0.05$). It is noteworthy that the interaction among SOA, spatial position, and group was significant, $F(4, 64) = 2.57$, $p < 0.05$, $\eta^2 = 0.14$.

For DD, there was a significant difference in the mean accuracy rate of the spatial position variable only for the SOA of 140 ms, $F(2, 18) = 6.70$, $p < 0.05$. Further analysis indicated that the mean accuracy rate of DD in the middle position was significantly lower than that in the left position, but there was no significant difference compared to the right position. Figure 2A presents the results. For CA, there was no significant difference in the mean accuracy rate of the spatial position variables for the SOAs of 140, 250, and 600 ms ($p > 0.05$) (Figure 2B). The research results indicate differences in the visual attention masking effects between DD and CA at different SOAs and spatial positions.

To comprehensively analyze the effects of the three different spatial positions on the visual attention engagement of the CA and DD, we adopted a repeated-measures ANOVA with SOA (140 and 250 ms vs. 600 ms) as the within-subject variable and group (DD and CA) as the between-subject variable. In the left position, the main effect of SOA was not significant,

Group	Experimental tasks									
	Single task	Dual task								
		Left			Middle			Right		
		40 ms	150 ms	500 ms	40 ms	150 ms	500 ms	40 ms	150 ms	500 ms
DD	0.76 ± 0.29	0.86 ± 0.19	0.90 ± 0.13	0.89 ± 0.21	0.63 ± 0.24	0.80 ± 0.27	0.86 ± 0.24	0.74 ± 0.30	0.72 ± 0.26	0.87 ± 0.24
CA	0.97 ± 0.07	0.98 ± 0.05	0.96 ± 0.07	10.00 ± 0.00	0.93 ± 0.11	0.95 ± 0.07	0.98 ± 0.05	0.96 ± 0.07	0.96 ± 0.07	0.94 ± 0.07

Table 1. Mean ± *SD* reaction times as a function of group, SOA, spatial position, and experimental tasks.

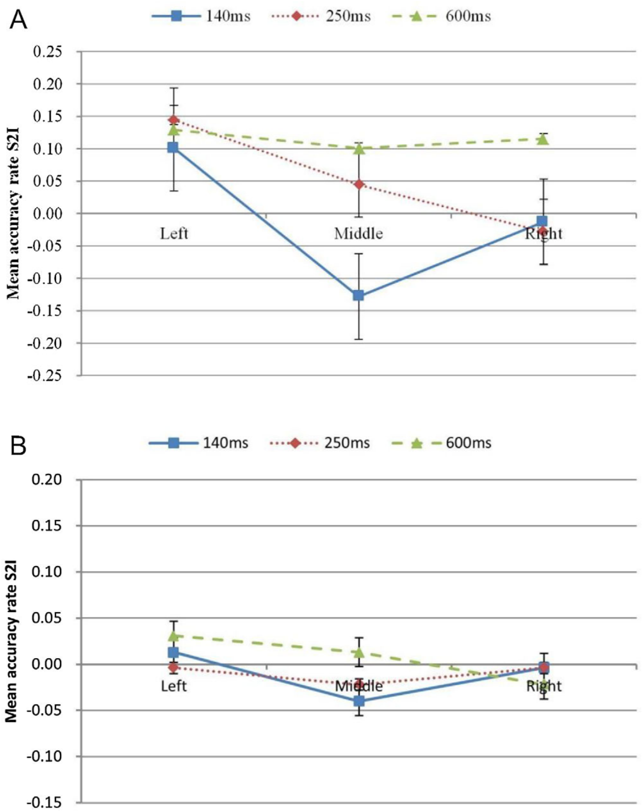

Figure 2. (**A**) Mean accuracy rate interference (S2I) for the different spatiotemporal distributions of visual attentional engagement for the DD group. S2I is plotted as a function of different temporal interval and spatial position conditions for Chinese children with dyslexia. *Error bars* depict standard errors of the means. (**B**) S2I in the different spatiotemporal distributions of visual attentional engagement for the CA group. S2I is plotted as a function of different temporal interval and spatial position conditions for CA. *Error bars* depict standard errors of the means.

$F(2, 32) = 0.29$, $p > 0.05$, $\eta^2 = 0.018$, nor was the main effect of group, $F(1, 16) = 1.67$, $p > 0.05$, $\eta^2 = 0.095$. Moreover, the interaction between SOA and group was not significant, $F(2, 32) = 0.58$, $p > 0.05$, $\eta^2 = 0.035$. Meanwhile, in the right position, the main effect of SOA and group was not significant, $F(2, 32) = 1.64$, $p > 0.05$, $\eta^2 = 0.093$; $F(1, 16) = 0.189$, $p > 0.05$, $\eta^2 = 0.012$, and the interaction between SOA and group was not significant, $F(2, 32) = 2.778$, $p > 0.05$, $\eta^2 = 0.148$.

More importantly, in the middle position, there was a significant main effect of SOA, $F(2, 32) = 10.63$, $p < 0.05$, $\eta^2 = 0.399$, reflecting larger AM effects for the 140-ms condition than the 250-ms and 600-ms conditions. The main effect of group was not significant, $F(1,16) = 0.096$, $p > 0.05$, $\eta^2 = 0.006$, but the interaction between SOA and group was significant, $F(2, 32) = 4.68$, $p < 0.05$, $\eta^2 = 0.227$, reflecting that the AM effect for the three different SOAs varied across

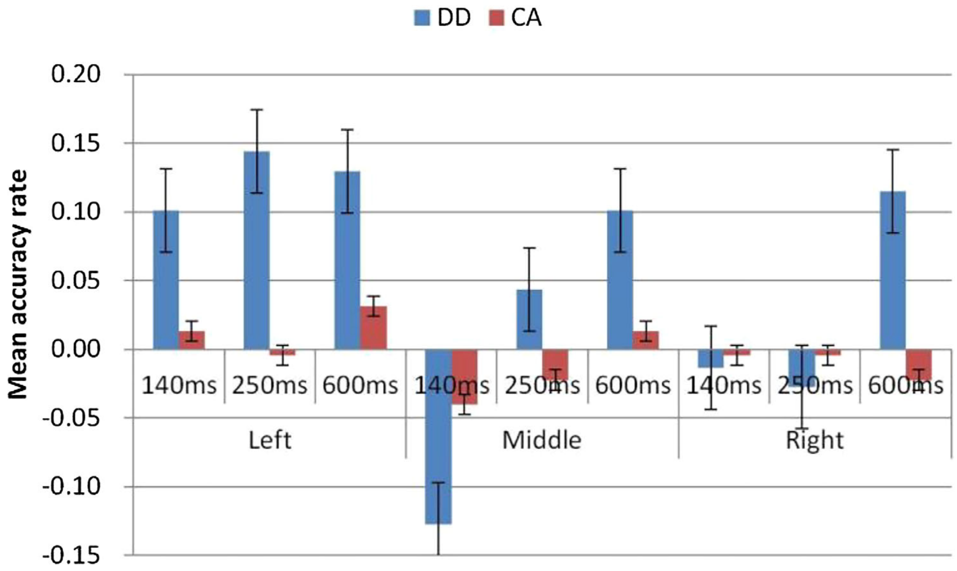

Figure 3. Mean accuracy rates for the different spatiotemporal distributions of visual attentional engagement for the DD and CA groups. The mean accuracy rates are plotted as a function of the different temporal interval and spatial position conditions for the different groups. *Error bars* depict standard errors of the means

groups. Specifically, for the DD group, SOA showed a significant effect on the AM effect, $F(2, 32) = 16.37$, $p < 0.05$, indicating that the AM effect was significantly larger for the 140-ms SOA than the 250-ms and 600-ms SOAs. In contrast, for the CA group, SOA had no significant effect on the AM effect, $F(2, 32) = 0.69$, $p > 0.05$ (Figure 3).

Discussion

The present study adopted the AM paradigm to investigate visual attentional engagement in Chinese children with dyslexia with a particular focus on the spatiotemporal distribution of attentional engagement deficits. In the baseline condition, the results showed that the differences were statistically significant for the DD and CA groups and that the mean accuracy rate of DD group was significantly lower than the CA group. More importantly, in the dual-task condition, there was a significant difference in the mean accuracy rate only for the 40-ms SOA. Specifically, the mean accuracy rate of the DD group in the middle position was significantly lower than that in the left position, but there was no significant difference compared to the right position. For the CA group, there was no significant difference in the mean accuracy rate of the spatial position among the different SOAs. Moreover, for the DD group, compared with the left and right positions, the AM effect was significantly larger in the 140-ms SOA than the 250-ms and 600 ms SOAs in the middle position. However, SOA had no significant effect on the effect of AM for the CA group. These results suggest that Chinese children with dyslexia are significantly impaired in visual attentional engagement and that spatiotemporal visual attentional engagement plays a special role in Chinese reading.

In the present study, we found that there were differences in visual attention masking effects between the DD and CA groups at different SOAs and spatial positions. This suggests that Chinese children with dyslexia might have a deficit in visual attentional engagement, especially in the spatiotemporal distribution of visual attentional engagement. As a logographic language, Chinese requires high visuospatial attentional engagement. This may be because Chinese characters are composed of multiple strokes or radicals within a two-dimensional space. Moreover, there are no word boundaries in Chinese texts, and effective temporal attention may help Chinese readers identify words or sentences in passage reading (Liu et al., 2015; Liu et al., 2016). Researchers have found a higher correlation between pure visual skills and word recognition in Chinese as compared with alphabetic orthographies (Ho & Bryant, 1999; Huang & Hanley, 1997; Mann, 1985). For Chinese reading, word recognition requires abstracting away from variations in size, font, and style. Doing so may be more difficult if visual processing is hampered by deficits in noise exclusion (Ji & Bi, 2020). Previous studies have found that children with dyslexia show larger AM at the shortest S1–S2 interval. In addition, specific language impairments lead to sluggish engagement in temporal attention (Dispaldro et al., 2013). Consistent with previous findings, the visual attention engagement deficits found in this study are particularly important with regard to reading by Chinese children with dyslexia compared with CA.

More importantly, we observed that the mean accuracy rate of the DD group in the middle position was significantly lower than that in the left position, but there was no significant difference between the middle and right positions, suggesting that Chinese children with dyslexia might have a deficit in attentional engagement of visual processing, particularly in spatiovisual attentional engagement. This finding is consistent with those of the related research results (Dispaldro et al., 2013; Ruffino et al., 2010). Moreover, converging evidence indicates an asymmetric distribution of visual attention between the left and right visual fields in children with dyslexia. For example, Hari et al. (2001) provided evidence that adults with dyslexia have a left visual field "mini-neglect" for stimuli. Facoetti and Turatto (2000) used a flanker task and found that individuals with dyslexia exhibit a reduced flanker effect in the left visual field. These results provide further support for the hypothesis of left-sided mini-neglect in individuals with dyslexia (Facoetti & Turatto, 2000). A large body of neuropsychological research indicates that the ventral regions of the right frontoparietal circuit are the cortical regions controlling multisensory attentional engagement in humans (Battelli, Pascual-Leone, & Cavanagh, 2007; Corbetta & Shulman, 2011). Several fMRI studies have shown predominantly right frontoparietal activation associated with the engagement of temporal attention (Giesbrecht & Kingstone, 2004; Marois, Chun, & Gore, 2000). Impaired processing of spatiotemporal multisensory attention engagement in children with dyslexia could be closely related with a dysfunction of the right inferior parietal cortex. In the present study, we also provide evidence of impaired attentional engagement of the left visual field in Chinese children with dyslexia.

Based on a comprehensive analysis, we also observed that Chinese children with dyslexia had larger AM than CA at the shortest S1–S2 interval, suggesting that their temporal selection of visual attentional engagement is inefficient. These results are in agreement with those of previous studies demonstrating that children with dyslexia have a specific impairment in visual attentional disengagement at shorter SOAs, but no significant cue effect in the cue–target paradigm compared to CA and adults (Facoetti et al., 2000; Facoetti et al., 2003a; Facoetti et al., 2005; Ruffino et al., 2014). This attention shifting can be considered to be the result of both engagement of processing resources onto the currently relevant target and disengagement of processing resources from the previously relevant target. When two visual stimuli are successively presented, they compete for the processing of attentional resources (Keysers & Perrett, 2002). Specifically, when the SOA between targets is short, S2 is often the first to be identified, but, as the SOAs increase, S1 is increasingly likely to be the first to be identified (Potter, Staub, & O'Connor, 2002). Therefore, S2 rapidly attracts the attentional processing resources, but, in the first perceptual stage, attentional engagement is labile.

At present, few studies have been conducted on visuospatial attention orienting in Chinese children with dyslexia. Duan et al. (2023) used the cue–target paradigm and reported that the impaired facilitation effect in Chinese children with dyslexia was due to developmental delay. Thus, it was suggested that Chinese children with dyslexia cannot shift and orient their attentional resources effectively at shorter SOAs over the time course of visual attentional engagement. A number of empirical studies have indicated that Chinese individuals with dyslexia have deficits in visual magnocellular pathway processing (Meng et al., 2022; Qian & Bi, 2014). Further studies have indicated that functioning of the magnocellular–dorsal pathway and the phonological awareness of children with dyslexia were improved to normal levels after intervention, whereas without intervention children with dyslexia saw no improvement, suggesting that magnocellular deficit might be the core deficit of Chinese children with dyslexia (Qian & Bi, 2015).

Additionally, in this study we considered the S1 identification mean accuracy rate under a single task as the baseline condition. Our results show that the S1 identification mean accuracy rate was significantly different between the DD and CA groups. Specifically, the DD group scored significantly lower than the CA group, suggesting that excessive visual crowding is often associated with dyslexia.

Crowding is defined as difficulty in recognizing objects surrounded by similar items (Gori & Facoetti, 2015). To date, several studies have suggested that children with dyslexia suffer from crowding more than CA readers do (Bouma & Legein, 1977; Callens, Whitney, Tops, & Brysbaert, 2013; Martelli, Di, Spinelli, & Zoccolotti, 2009; Moll & Jones, 2013). Two theories have been proposed to explain this phenomenon. One argues that visual crowding could be the result of a limited resolution of spatial attention (Intriligator & Cavanagh, 2001; Strasburger, 2005; Yeshurun & Rashal, 2010). The other theory suggests that visual crowding usually occurs in the time domain (Whitney & Levi, 2011), and that the effects of spatial crowding are correlated with those of temporal crowding (Bonneh, Sagi, & Polat, 2007). The results of the present study support the proposal that spatiotemporal and attentional mechanisms are involved in visual crowding.

Another possible reason for the S1 identification mean accuracy rates differing between the DD and CA groups might be the perceptual noise exclusion deficit in dyslexia (Sperling, Lu, Manis, & Seidenberg, 2005). This hypothesis describes an impaired ability to filter out visual perceptual noise to distinguish relevant sensory signals from irrelevant ones. A recent study by Ji and Bi (2020) reported that Chinese children with dyslexia showed poorer performance than controls in only the high-noise condition, no matter what kind of stimuli types and tasks they processed. These results suggest that Chinese children with dyslexia have a noise exclusion deficit, and the present study supports this perceptual noise exclusion hypothesis.

In summary, we systematically manipulated a visual attention masking task to investigate the impact of spatiotemporal distribution on visual attention engagement in Chinese children with dyslexia. The findings of the present study contribute to the literature on visuospatial attention disengagement and visual attention engagement in Chinese children with dyslexia. The present investigation did have some limitations that should be addressed in future research. First, in order to control the visual perceptual abilities of a single object (S1) in the single-task condition, the participants had to identify the object and choose from among four possible experimental stimuli displayed on the screen. Therefore, the familiarity effect of identifying the object (S1) in the single-task condition might have influenced the mean accuracy rate in the dual-task condition. Second, a possible reason why the presentation of a second object improved recognition of the first in the dual-task condition might be the lower level of difficulty of the experimental stimuli. The participants were required to identify the object (S1) by choosing among the four possible experimental stimuli displayed on the screen. This could have resulted in a possible ceiling effect in the dual-task condition for the DD and CA groups, so future studies will use more complex tasks. Third, to date, there still is almost no direct evidence of a deficit in visual attention engagement in DD. In the future, this issue could be resolved using more accurate neurophysiological measurements.

Keywords: developmental dyslexia, visual attention engagement, visual attentional masking, chinese reading

Acknowledgments

We thank Editage (www.editage.cn) for English language editing, and we thank all of the children, their parents, and their teachers for their participation.

Supported by a doctoral research initiation project of Hexi University (KYQD2020042).

Commercial relationships: none.

Corresponding author: Aibao Zhou.
Email: zhouab@nwnu.edu.cn.
Address: School of Psychology, Northwest Normal University, Lanzhou 730070, China.

References

Battelli, L., Pascual-Leone, A., & Cavanagh, P. (2007). The ‘when’ pathway of the right parietal lobe. *Trends in Cognitive Sciences, 11*(5), 204–210.

Bertoni, S., Andreola, C., Mascheretti, S., Franceschini, S., Ruffino, M., Trezzi, V., . . . Facoetti, A. (2024). Action video games normalise the phonemic awareness in pre-readers at risk for developmental dyslexia. *NPJ Science of Learning, 9*(1), 25.

Bertoni, S., Franceschini, S., Campana, G., & Facoetti, A. (2023). The effects of bilateral posterior parietal cortex tRNS on reading performance. *Cerebral Cortex, 33*(9), 5538–5546.

Bertoni, S., Franceschini, S., Puccio, G., Mancarella, M., Gori, S., & Facoetti, A. (2021). Action video games enhance attentional control and phonological decoding in children with developmental dyslexia. *Brain Sciences, 11*(2), 171.

Boyer, J., & Ro, T. (2007). Attention attenuates metacontrast masking. *Cognition, 104*(1), 135–149.

Bonneh, Y. S., Sagi, D., & Polat, U. (2007). Spatial and temporal crowding in amblyopia. *Vision Research, 47*(14), 1950–1962.

Bouma, H., & Legein, C. P. (1977). Foveal and parafoveal recognition of letters and words by dyslexics and by average readers. *Neuropsychologia, 15*(1), 69–80.

Brannan, J. R., & Williams, M. C. (1987). Allocation of visual attention in good and poor readers. *Perception & Psychophysics, 41*(1), 23–28.

Callens, M., Whitney, C., Tops, W., & Brysbaert, M. (2013). No deficiency in left-to-right processing of words in dyslexia but evidence for enhanced visual crowding. *Quarterly Journal of Experimental Psychology, 66*(9), 1803–1817.

Carrasco, M., Williams, P. E., & Yeshurun, Y. (2002). Covert attention increases spatial resolution with or without masks: Support for signal enhancement. *Journal of Vision, 2*(6):4, 467–479, https://doi.org/10.1167/2.6.4.

Corbetta, M., & Shulman, G. L. (2011). Spatial neglect and attention networks. *Annual Review of Neuroscience, 34*(1), 569–599.

Di Lollo, V., Hanson, D., & McIntyre, J. S. (1983). Initial stages of visual information processing in dyslexia. *Journal of Experimental Psychology: Human Perception and Performance, 9*(6), 923–935.

Ding, Y., Zhao, J., He, T., Tan, Y., Zheng, L., & Wang, Z. (2016). Selective impairments in covert shifts of attention in Chinese dyslexic children. *Dyslexia, 22*(4), 362–378.

Dispaldro, M., Leonard, L. B., Corradi, N., Ruffino, M., Bronte, T., & Facoetti, A. (2013). Visual attentional engagement deficits in children with specific language impairment and their role in real-time language processing. *Cortex, 49*(8), 2126–2139.

Dosher, B. A., & Lu, Z. L. (2000). Noise exclusion in spatial attention. *Psychological Science, 11*(2), 139–146.

Duan, B., Wang, D., Li, W., Ma, X., & Zhou, A. (2023). The impairment of the visual-spatial attention in Chinese children with dyslexia: A cognitive deficit or a developmental delay? *Current Psychology, 42*(6), 4341–4349.

Enns, J. T., & Di Lollo, V. (2000). What's new in visual masking? *Trends in Cognitive Sciences, 4*(9), 345–352.

Facoetti, A., Lorusso, M. L., Cattaneo, C., Galli, R., & Molteni, M. (2005). Visual and auditory attentional capture are both sluggish in children with developmental dyslexia. *Acta Neurobiologiae Experimentalis, 65*(1), 61–72.

Facoetti, A., Lorusso, M. L., Paganoni, P., Cattaneo, C., Galli, R., & Mascetti, G. G. (2003a). The time course of attentional focusing in dyslexic and normally reading children. *Brain and Cognition, 53*(2), 181–184.

Facoetti, A., Lorusso, M. L., Paganoni, P., Cattaneo, C., Galli, R., Umiltà, C., … Mascetti, G. G. (2003b). Auditory and visual automatic attention deficits in developmental dyslexia. *Cognitive Brain Research, 16*(2), 185–191.

Facoetti, A., Lorusso, M. L., Paganoni, P., Umiltà, C., & Mascetti, G. G. (2003c). The role of visuospatial attention in developmental dyslexia: Evidence from a rehabilitation study. *Cognitive Brain Research, 15*(2), 154–164.

Facoetti, A., Paganoni, P., Turatto, M., Marzola, V., & Mascetti, G. G. (2000). Visual-spatial attention in developmental dyslexia. *Cortex, 36*(1), 109–123.

Facoetti, A., Ruffino, M., Peru, A., Paganoni, P., & Chelazzi, L. (2008). Sluggish engagement and disengagement of non-spatial attention in dyslexic children. *Cortex, 44*(9), 1221–1233.

Facoetti, A., & Turatto, M. (2000). Asymmetrical visual fields distribution of attention in dyslexic children: A neuropsychological study. *Neuroscience Letters, 290*(3), 216–218.

Franceschini, S., Bertoni, S., Puccio, G., Gori, S., Termine, C., & Facoetti, A. (2022). Visuo-spatial attention deficit in children with reading difficulties. *Scientific Reports, 12*(1), 13930.

Franceschini, S., Gori, S., Ruffino, M., Pedrolli, K., & Facoetti, A. (2012). A causal link between visual spatial attention and reading acquisition. *Current Biology, 22*(9), 814–819.

Franceschini, S., Gori, S., Ruffino, M., Viola, S., Molteni, M., & Facoetti, A. (2013). Action video games make dyslexic children read better. *Current Biology, 23*(6), 462–466.

Fu, W., Zhao, J., Ding, Y., & Wang, Z. (2019). Dyslexic children are sluggish in disengaging spatial attention. *Dyslexia, 25*(2), 158–172.

Giesbrecht, B., & Kingstone, A. (2004). Right hemisphere involvement in the attentional blink: Evidence from a split-brain patient. *Brain and Cognition, 55*(2), 303–306.

Gori, S., & Facoetti, A. (2015). How the visual aspects can be crucial in reading acquisition? The intriguing case of crowding and developmental dyslexia. *Journal of Vision, 15*(1):8, 1–20, https://doi.org/10.1167/15.1.8.

Hari, R., Renvall, H., & Tanskanen, T. (2001). Left mini-neglect in dyslexic adults. *Brain, 124*(7), 1373–1380.

Ho, C. S. H., & Bryant, P. (1999). Different visual skills are important in learning to read English and Chinese. *Educational and Child Psychology, 16*(4), 4–14.

Huang, H. S., & Hanley, J. R. (1997). A longitudinal study of phonological awareness, visual skills, and Chinese reading acquisition among first-graders in Taiwan. *International Journal of Behavioral Development, 20*(2), 249–268.

Intriligator, J., & Cavanagh, P. (2001). The spatial resolution of visual attention. *Cognitive Psychology, 43*(3), 171–216.

Ji, Y., & Bi, H. Y. (2020). Visual dysfunction in Chinese children with developmental dyslexia: Magnocellular-dorsal pathway deficit or noise exclusion deficit? *Frontiers in Psychology, 11*, 483941.

Keysers, C., & Perrett, D. I. (2002). Visual masking and RSVP reveal neural competition. *Trends in Cognitive Sciences, 6*(3), 120–125.

Krause, M. B. (2015). Pay attention!: Sluggish multisensory attentional shifting as a core deficit in developmental dyslexia. *Dyslexia, 21*(4), 285–303.

Li, Y., & Bi, H. Y. (2022). Comparative research on neural dysfunction in children with dyslexia under different writing systems: A meta-analysis study. *Neuroscience & Biobehavioral Reviews, 137*, 104650.

Liu, D., Chen, X., & Chung, K. K. H. (2015). Performance in a visual search task uniquely predicts reading abilities in third-grade Hong Kong Chinese children. *Scientific Studies of Reading, 19*(4), 307–324.

Liu, D., Chen, X., & Wang, Y. (2016). The impact of visual-spatial attention on reading and spelling in Chinese children. *Reading and Writing, 29*(7), 1435–1447.

Liu, S., & Liu, D. (2020). Visual-spatial attention and reading achievement in Hong Kong Chinese children: Evidence from a one-year longitudinal study. *Scientific Studies of Reading, 24*(3), 214–228.

Liu, S., Liu, D., Pan, Z., & Xu, Z. (2018). The association between reading abilities and visual-spatial attention in Hong Kong Chinese children. *Dyslexia, 24*(3), 263–275.

Liu, S., Xu, Z., & Liu, D. (2023). The effects of stimulus–driven and goal–directed attentional control on word reading skills among first grade Chinese children. *Journal of Research in Reading, 46*(1), 104–121.

Liu, Y. F., Qian, Y., & Bi, H. Y. (2022). Visual motion processing in Chinese children with developmental dyslexia: An fMRI study. *Dyslexia, 28*(4), 431–447.

Lyon, G. R., Shaywitz, S. E., & Shaywitz, B. A. (2003). A definition of dyslexia. *Annals of Dyslexia, 53*(1), 1–14.

Mann, V. A. (1985). A cross-linguistic perspective on the relation between temporary memory skills and early reading ability. *Remedial and Special Education, 6*(6), 37–42.

Marois, R., Chun, M. M., & Gore, J. C. (2000). Neural correlates of the attentional blink. *Neuron, 28*(1), 299–308.

Martelli, M., Di, F. G., Spinelli, D., & Zoccolotti, P. (2009). Crowding, reading, and developmental dyslexia. *Journal of Vision, 9*(4):14, 1–18, https://doi.og/10.1167/9.4.14.

McBride-Chang, C., Chow, B. W. Y., Zhong, Y., Burgess, S., & Hayward, W. G. (2005). Chinese character acquisition and visual skills in two Chinese scripts. *Reading and Writing, 18*(2), 99–128.

McBride-Chang, C., Zhou, Y., Cho, J. R., Aram, D., Levin, I., & Tolchinsky, L. (2011). Visual spatial skill: A consequence of learning to read? *Journal of Experimental Child Psychology, 109*(2), 256–262.

Meng, Z. L., Liu, M. L., & Bi, H. Y. (2022). Spatial and temporal processing difficulties in Chinese children with developmental dyslexia: An ERP study. *Dyslexia, 28*(4), 416–430.

Moll, K., & Jones, M. (2013). Naming fluency in dyslexic and non-dyslexic readers: Differential effects of visual crowding in foveal, parafoveal, and peripheral vision. *Quarterly Journal of Experimental Psychology, 66*(11), 2085–2091.

Potter, M. C., Staub, A., & O'Connor, D. H. (2002). The time course of competition for attention: attention is initially labile. *Journal of Experimental Psychology: Human Perception and Performance, 28*(5), 1149.

Qian, Y., & Bi, H. Y. (2014). The visual magnocellular deficit in Chinese-speaking children with developmental dyslexia. *Frontiers in Psychology, 5*, 692.

Qian, Y., & Bi, H. Y. (2015). The effect of magnocellular-based visual-motor intervention on Chinese children with developmental dyslexia. *Frontiers in Psychology, 6*, 1529.

Raven, J., Raven, J. C., & Court, C. (1998). *Manual for Raven's progressive matrices and vocabulary scales*. Oxford: Oxford Psychologists Press.

Ruffino, M., Gori, S., Boccardi, D., Molteni, M., & Facoetti, A. (2014). Spatial and temporal attention in developmental dyslexia. *Frontiers in Human Neuroscience, 8*, 331.

Ruffino, M., Trussardi, A. N., Gori, S., Finzi, A., Giovagnoli, S., Menghini, D., … Facoetti, A. (2010). Attentional engagement deficits in dyslexic children. *Neuropsychologia, 48*(13), 3793–3801.

Shaywitz, S. E., & Shaywitz, B. A. (2005). Dyslexia (specific reading disability). *Biological Psychiatry, 57*(11), 1301–1309.

Shu, H., McBride-Chang, C., Wu, S., & Liu, H. (2006). Understanding Chinese developmental dyslexia: Morphological awareness as a core cognitive construct. *Journal of Educational Psychology, 98*(1), 122–133.

Sperling, A. J., Lu, Z. L., Manis, F. R., & Seidenberg, M. S. (2005). Deficits in perceptual noise exclusion in developmental dyslexia. *Nature Neuroscience, 8*(7), 862–863.

Stein, J., & Walsh, V. (1997). To see but not to read; the magnocellular theory of dyslexia. *Trends in Neurosciences, 20*(4), 147–152.

Strasburger, H. (2005). Unfocussed spatial attention underlies the crowding effect in indirect form vision. *Journal of Vision, 5*(11):8, 1–13, https://doi.org/10.1167/5.11.8.

Vidyasagar, T. R., & Pammer, K. (2010). Dyslexia: A deficit in visuo-spatial attention, not in phonological processing. *Trends in Cognitive Sciences, 14*(2), 57–63.

Visser, T. A., Boden, C., & Giaschi, D. E. (2004). Children with dyslexia: Evidence for visual attention deficits in perception of rapid sequences of objects. *Vision Research, 44*(21), 2521–2535.

Whitney, D., & Levi, D. M. (2011). Visual crowding: A fundamental limit on conscious perception and object recognition. *Trends in Cognitive Sciences, 15*(4), 160–168.

Yang, T., Cai, Y., Liu, H., & Liu, X. (2023). The nature of paired associate learning deficits in Chinese children with developmental dyslexia. *Brain Sciences, 13*(2), 172.

Yeh, S. L., & Li, J. L. (2002). Role of structure and component in judgments of visual similarity of Chinese characters. *Journal of Experimental Psychology: Human Perception and Performance, 28*(4), 933–947.

Yeshurun, Y., & Rashal, E. (2010). Precueing attention to the target location diminishes crowding and reduces the critical distance. *Journal of Vision, 10*(10):16, 1–12, https://doi.org/10.1167/10.10.16.

Yu, L., Zhang, Q., Priest, C., Reichle, E. D., & Sheridan, H. (2018). Character-complexity effects in Chinese reading and visual search: A comparison and theoretical implications. *Quarterly Journal of Experimental Psychology, 71*(1), 140–151.

Zhang, H., & Wang, X. (1985). *Raven's IQ reasoning standardized test*. Beijing: Department of Psychology, Beijing Normal University Press.