DYSLEXIA
Published online in Wiley Online Library
(wileyonlinelibrary.com). DOI: 10.1002/dys.1541

Selective Impairments in Covert Shifts of Attention in Chinese Dyslexic Children

Yun Ding[1,2], Jing Zhao[1,2]*, Tao He[1,2], Yufei Tan[1,2], Lingshuang Zheng[1,2] and Zhiguo Wang[1,2,3]

[1]*Institute of Psychological Sciences, Hangzhou Normal University, Hangzhou, China*
[2]*Zhejiang Key Laboratory for Research in Assessment of Cognitive Impairments, Hangzhou, China*
[3]*Department of Cognitive Science, Macquarie University, Sydney, Australia*

Reading depends heavily on the efficient shift of attention. Mounting evidence has suggested that dyslexics have deficits in covert attentional shift. However, it remains unclear whether dyslexics also have deficits in overt attentional shift. With the majority of relevant studies carried out in alphabetic writing systems, it is also unknown whether the attentional deficits observed in dyslexics are restricted to a particular writing system. The present study examined inhibition of return (IOR)—a major driving force of attentional shifts—in dyslexic children learning to read a logographic script (i.e., Chinese). Robust IOR effects were observed in both covert and overt attentional tasks in two groups of typically developing children, who were age- or reading ability-matched to the dyslexic children. In contrast, the dyslexic children showed IOR in the overt but not in the covert attentional task. We conclude that covert attentional shift is selectively impaired in dyslexic children. This impairment is not restricted to alphabetic writing systems, and it could be a significant contributor to the difficulties encountered by children learning to read. Copyright © 2016 John Wiley & Sons, Ltd.

Keywords: attention; developmental dyslexia; Posner cueing task; visual search; eye movements; inhibition of return

INTRODUCTION

Learning to read is a marvelous achievement in child development. Most children master reading in a few years of schooling. In about 5–10% of children, however, learning to read is extremely challenging and eventually results in developmental dyslexia (DD), a specific learning disorder in reading acquisition in the presence of adequate intelligence, conventional education, and normal sociocultural context (American Psychiatric Association, 2013; Shaywitz & Shaywitz, 2005). The efficient shift of attention is indispensable to rapid and sequential selection of sublexical orthographic units (Facoetti *et al*., 2006; Facoetti, Trussardi, *et al*., 2010; Ruffino *et al*., 2010; for a computational account, see Perry *et al*., 2007). While the

---

*Correspondence to: Jing Zhao, Institute of Psychological Sciences, Hangzhou Normal University, 2318 Yuhangtang Rd., Hangzhou 311121, China. E-mail zhaojing561@126.com

This project was supported by grants from the National Natural Science Foundation of China (NSFC) to J. Zhao (grant No.: 81301175) and Z. Wang (grant No.: 31371133).

dominant view in the field maintains that dyslexia originate from deficits in phonological processing (for reviews, see Snowling, 2000; Vellutino *et al.*, 2004), bourgeoning evidence shows that developmental reading difficulties may as well arise from dysfunctions in attention (Valdois *et al.*, 2004; Vidyasagar & Pammer, 2010; for reviews and discussions, see Krause, 2015; Zhou *et al.*, 2014). In line with these findings, recent studies have shown that the efficiency of attentional orienting is a strong predictor of reading development (e.g., Facoetti, Corradi, Ruffino, Gori, & Zorzi, 2010; Ferretti *et al.*, 2008; Plaza & Cohen, 2007), and the reading performance of dyslexic children significantly improves following training in attentional shift (e.g., Facoetti, Lorusso, Paganoni, Umiltà, & Gastone Mascetti, 2003).

According to the 'sluggish attentional shift' hypothesis (Hari & Renvall, 2001), the primary attentional problem of dyslexics is that they have difficulty in disengaging attention from the currently attended location. Direct empirical evidence for this hypothesis comes from studies that revealed inhibition of return (IOR) in normal developing but not in dyslexic children (e.g., Facoetti *et al.*, 2003). First discovered by Posner and Cohen (1984) in a spatial cueing paradigm (Posner, 1980), IOR is widely regarded as an attentional mechanism that biases against previously inspected locations (e.g., Koch & Ullman, 1985; Posner & Cohen, 1984) and encourages orienting towards novelty in visual foraging tasks (e.g., Klein, 1988; Klein & MacInnes, 1999). Studies of IOR in developmental, ageing, and schizophrenia populations all suggest that the absence of IOR is a strong indication of difficulty or deficiency in attentional disengagement (for a review, see Klein, 2005). In dyslexics, a difficulty in attentional disengagement would have impeded visual sampling, and consequently, slowed down letter-to-sound conversion (Facoetti, Lorusso, *et al.*, 2003; Facoetti, Trussardi, *et al.*, 2010; Facoetti *et al.*, 2006; Roach & Hogben, 2008).

To gain a thorough understanding of the attentional dysfunctions in dyslexics, it is important to distinguish two forms of attentional control (Klein, 2005; Klein *et al.*, 1992; Posner, 1980). Covert attentional orienting is the implicit allocation of attentional resources to features or objects in the environment, in the absence of eye movements. Overt attentional orienting, on the other hand, is the conscious selection of regions of space for detailed processing by the most sensitive part of the retina (i.e., fovea), and usually involves the shift of gaze. While most previous studies focus primarily on dyslexics' dysfunctions in covert attentional control, some recent empirical work indicates that dyslexics may also have dysfunctions in overt attentional control. For instance, dyslexics have poor ability in gaze control in several non-reading situations (Crawford & Higham, 2001; Fischer *et al.*, 2000). More importantly, a recent study has revealed that the size of regressive saccades during reading correlates with IOR effects measured in a non-reading task (Weger & Inhoff, 2006), implicating that the inefficiency of gaze control in dyslexics may closely relate to IOR. The primary purpose of the present study was to clarify whether IOR—a major driving force of attentional shifts—is abnormal in tasks that require the overt shift of attention (i.e., gaze shifts) in dyslexics. To this end, in addition to the classic Posner cueing task in which eye movements are discouraged (Posner, 1980; Posner & Cohen, 1984), IOR was also assessed in a challenging visual search task that required gaze-shifts (e.g., Klein & Macinnes, 1999; Smith & Henderson, 2011; Thomas *et al.*, 2006; see Wang & Klein, 2010, for a review).

In addition to examining IOR in an overt attentional task, the present study also has two other features that make it an important and timely contribution to the field. First, recent evidence has shown that orthographic depth mediates the role of visual attention in reading (Bavelier *et al*., 2013; Richlan, 2014; see Zhou *et al*., 2014, for a review). Studies examining the attentional dysfunctions in dyslexics, however, have been all carried out in alphabetic scripts. Chinese characters are dramatically different from alphabetic scripts in terms of form (Li *et al*., 2009; Yeh & Li, 2002), orthography (Chen & Kao, 2002), and phonology (Leck *et al*., 1995). An examination of IOR in Chinese dyslexic children is much needed to clarify whether attentional dysfunctions underlie DD across different writing systems. Second, as has been alluded to before, recent studies suggested that a deficiency in attentional shift may be a causal factor for reading difficulties (for a discussion, see Facoetti, Trussardi, *et al*., 2010; Franceschini *et al*., 2012). To verify whether this conjecture also holds in Chinese dyslexic children, the present study adopted a 'reading level match' design (Backman *et al*., 1984; Bryant & Bradley, 1985; Bryant & Goswami, 1986; Goswami, 2003). In addition to children with DD and normal developing children of the same chronological age (CA), a group of children of the same reading level (RL) as, but were two years younger than the dyslexic children was also tested. If the deficiency in attentional shift is indeed a causal factor for DD, IOR should be absent in dyslexic children, but not in reading level-matched normal developing children, who were two years younger.

METHOD

The research protocol reported here was approved by an institutional review board of authors' institution. Written informed consent was obtained from the parents of all children who participated in the present experiments.

To assess IOR following covert and overt attentional orienting, participants were encouraged to complete both a cueing task and a visual search task. These two tasks were completed in a single session and were counterbalanced across participants.

Participants

Fifty-four first and third grade children from a local elementary school took part in this study. All of them were native Chinese speakers, who had normal or corrected-to-normal visual acuity. Three children were excluded from analyses because they did not finish all experimental tasks; another four children were excluded from analyses because their teachers reported that they had ADHD symptoms. So, the data reported in the present paper were based on a total of 47 children, aged between 6.6 and 10.8 years. Of these children, 15 children were classified as having DD (DD group; 9 boys, 6 girls) and 32 were typically developing children. Of the typically developing children, 17 had the same chronological age as the dyslexic children (CA group; 12 boys, 5 girls), and 15 had the same reading level as the dyslexic children (RL group; 7 boys, 8 girls). The CA and DD children were from the third grade and the RL children were from the first grade.

These three groups of children were selected with the Standard Combined Raven's Test (CRT; Li & Chen, 1989), and a Chinese character recognition test (Shu *et al*., 2003), which has been widely used for screening Mandarin-speaking Chinese children for dyslexia (e.g., Lei *et al*., 2011; Li *et al*., 2009; Shu *et al*., 2006; Zhang *et al*., 2012). In the character recognition test, children were instructed to read a list of 150 Chinese characters arranged in increasing difficulty and their reading errors were recorded (see Shu *et al*., 2003, for a detailed description). As in previous studies of Chinese developmental dyslexics (e.g., Ho *et al*., 2004; Li *et al*., 2009; Wang & Yang, 2011; Zhang *et al*., 2012), for a child to be included in the DD group, he/she should have normal intelligence and his/her scores on the character recognition test should be at least one standard deviation below the average of the same grade.

The demographic characteristics of the participants and their performance on the CRT test and the Chinese character recognition test are presented in Table 1. Welch's *t* tests revealed that the mean age of the DD group did not differ from that of the CA group, $t(23) = 0.23$, $p = 0.82$, Cohen's $d = 0.08$, but was older than that of the RL group, $t(20) = 11.42$, $p < 0.001$, Cohen's $d = 4.05$. As is clear from this table, no difference in the CRT test was found between the DD, CA, and RL groups, $F(2, 44) = 1.$, MSE = 183.9, $p = 0.21$, $\eta_G^2 = 0.07$.[1] For the Chinese character recognition test, the RL group performed as good as the DD group, $t(17) = 0.28$, $p = 0.79$, Cohen's $d = 0.10$; both the RL and DD groups made significantly more errors than the CA group, all $t > 9.97$, all $p < 0.001$, all Cohen's $d > 3.53$.

Task to Assess IOR Following Covert Attentional Orienting

The classic Posner cueing task (Posner & Cohen, 1984) was adopted to assess IOR following covert attentional orienting.

Stimuli and Apparatus

Stimuli were presented on a 19-inch NESO FS210A CRT monitor, and the viewing distance (62 cm) was controlled with a chinrest. Stimulus presentation and data registration were controlled by a PC, running scripts written in Python. Eye movements were monitored with a desktop mounted EyeLink 1000 eye-tracker (SR Research®). The spatial resolution of the eye tracker was 0.2° or better, and the participant's gaze position was sampled at 1000 Hz.

Table 1. Mean ages and scores on the CRT test and the Chinese character recognition test. Numbers in the parentheses are SDs. Scores on the character recognition task are the total number of misnamed characters. DD, children with developmental dyslexia; CA, typically developing children, age matched to the DD group; RL, typically developing children, reading-level matched to the DD group

Group	*N*	Age (years)	CRT	Character recognition errors
DD	15	9.09 (0.63)	112.27 (15.11)	76.80 (6.20)
CA	17	9.13 (0.38)	119.11 (12.94)	28.88 (4.48)
RL	15	7.07 (0.29)	120.57 (12.58)	75.47 (17.59)

Two gray boxes that subtended 1.8° visual angle were used as placeholders in the cueing task (see Figure 1). These boxes were placed horizontally across the centre of the screen and their distance to the central fixation was 9°. The cue was implemented as the brightening and thickening of one of the peripheral boxes. The target was a bright, filled circle, with a diameter of 1°.

Procedure and Design

The sequence of events in the cueing task is illustrated in Figure 1. Self-paced drift correction was performed at the beginning of each trial, and successful drift correction was signalled by a beep. Following successful drift correction, two gray boxes (place holders) appeared on the screen, together with a fixation cross at the screen center. One thousand milliseconds later, the cue was presented at the left, right, or both peripheral boxes for 100 ms. We used a 600-ms cue-target onset asynchrony (CTOA); it was relatively longer than the ordinary IOR studies because some studies suggest that longer CTOAs are needed to observe IOR in younger children compared to adolescents and adults (Facoetti, Lorusso, *et al.*, 2003). To minimize the effect of temporal expectations on response times (RTs), the target was presented 550, 600, or 650 ms later (randomly selected for each trial). The target appeared in one of the two peripheral boxes, and the participant had 1500 ms to respond with the space bar on a standard QWERTY keyboard. To discourage anticipatory responses, the target was not presented on 25% of the trials. When the target was presented, it could appear in the cued box (valid-cue) or in the box opposite to the cue (invalid-cue) if preceded by one cue, or it could appear in either peripheral box if preceded by cues at both peripheral boxes (neutral-cue). These three types of cue–target combinations were presented with equal probability.

The cueing task consisted of three blocks of 48 trials. A standard nine-point calibration of the eye tracker was performed at the beginning of each block, or

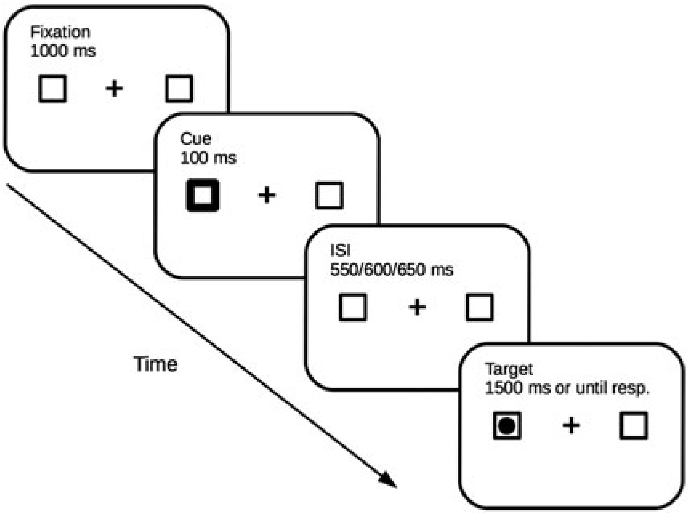

Figure 1. Sequence of events in a sample trial in the cueing task. The cue could appear at the left, right, or both peripheral boxes.

whenever a break was required by the participant. The participants were explicitly instructed to maintain fixation throughout a trial. The experimenter would remind the participant to keep fixating if fixation was broken on two successive trials.

Data Analysis

In cueing tasks, IOR effect is typically quantified with the RT difference between valid-cue and invalid-cue trials. Several lines of evidence have suggested that because the cueing task involves repeated stimulation of the same retinal locus, the IOR effect measured in such tasks may partially attributable to short-term depression or habituation of the early visual pathway (Dukewich, 2009; Patel *et al.*, 2010; Satel *et al.*, 2011), rather than a cost of returning attention. This potential confound can be easily avoided by using trials with double cues (i.e., neutral-cue trials in the present experiment) as baseline for calculating IOR. Because the target location is also stimulated on neutral-cue trials, the RT difference between valid- and neutral-cue trials provides an alternative behavioural index of IOR. Furthermore, previous studies have demonstrated that, in cueing tasks, the location inhibited by IOR is determined by the net vector of the cue(s) (Christie *et al.*, 2013; Klein *et al.*, 2005). With two cues flanking the central fixation, as was on neutral-cue trials in the present experiment, because the net vector of the cues is at fixation, neither of the cued locations would be inhibited by IOR. However, because neutral-cue trials had two cues whereas valid-cue trials had only one, it is likely that the participant's mental set at the time of the target onset would differ between these two types of trials (Jonides & Mack, 1984). For these considerations, we will report IOR effects measured as the RT difference between valid- and neutral-cue trials as well as that between valid- and invalid-cue trials.

Task to Assess IOR Following Overt Attentional Orienting

To assess IOR following overt attentional orienting, a visual search task that typically involves a series of rapid eye movements (e.g., Klein & Macinnes, 1999; Smith & Henderson, 2011; Thomas *et al.*, 2006) was adopted in the present study. In this task, IOR is manifested by longer latencies and lower probabilities for saccades returning to previously fixated, and thus attended, locations.

Stimuli and Apparatus

Similar to previous studies (Klein & Macinnes, 1999; Smith & Henderson, 2011), participants were required to search for a camouflaged target—a distinctively dressed cartoon character named 'Waldo'—from 30 unique full-colour pictures adapted from the 'Where's Waldo?' series by Martin Handford (1987). These pictures depicted highly cluttered scenes, containing many colourful background elements as well as human figures. A series of rapid eye movements (saccades) are usually generated before Waldo is successfully found, and thus this task will be referred to as an 'oculomotor search task'.

Stimuli were presented on a 21-inch CRT monitor. Stimulus timing and response registration were controlled by custom scripts written in Python. Eye movements were monitored and recorded with an MRI-compatible Eyelink 1000 (SR Research®) eye-tracker. The spatial resolution of this eye-tracker was 0.2°

or better, and the sampling rate was set to 1000 Hz. The viewing distance was maintained at about 71 cm with a chinrest.

Procedure and Design

A trial started with the presentation of a fixation dot. When the participant's gaze was within 1° of the fixation dot, the experimenter started the presentation of the search scene by pressing the space bar on a keyboard connected to the Eyelink server. Participants were instructed to search for Waldo and to press the space bar when they found Waldo. They were allowed to search each scene for a maximum of 10 s. At the beginning of this task, examples of Waldo were shown to the participants to help them to get familiar with Waldo. This task had 30 trials, and the target (Waldo) was present on 10 trials.

Data Analysis

The purpose of this visual search task was not to assess how efficiently the participant identified the search target (Waldo), but rather to examine the saccades executed during search. Based on previous IOR studies, saccades returning to the vicinity of previous fixations were expected to have longer latencies and lower probabilities than those to distance matched control locations. To quantify IOR at the immediate preceding (1-back) and the penultimate (2-back) fixations, the latency and probability of saccades landing at the 1-back and 2-back fixations were compared to that of those landing in three distance matched locations 90°, 180°, and 270° (angular distance) away (see Figure 2, for an illustration). We examined only saccades that landed within 1° of these four locations (see also Smith & Henderson, 2011).

RESULTS

IOR Following Covert Attentional Orienting

The classic Posner cueing task was used to assess IOR following covert attentional orienting. False alarm rates in this task were 1.30%, 2.29%, and 3.52% for the DD, CA, and RL groups, respectively. These false alarm rates were too low to warrant further analysis. To avoid potential contribution of oculomotor processes to IOR (e.g., Hilchey *et al.*, 2014), trials on which eye movements were detected were not considered in our analyses. These excluded trials accounted for 25.51%, 28.19%, and 28.06% of the trials tested in the DD, CA, and RL groups. Analysis showed that the number of trials excluded because of eye movements did not differ across groups, $F(2, 44) = 0.19$, $\mathrm{MSE} = 381.5$, $p = 0.83$, $\eta_G^2 = 0.01$. RTs of the remaining trials were cleaned based on the number of trials in each experimental cell of each participant, following the criteria given by Van Selst and Jolicoeur (1994, Table 4). This data cleaning procedure excluded 2.88%, 2.88%, and 2.18% trials for the DD, CA, and RL groups, respectively. The number of excluded trials with this procedure again did not differ across groups, $F(2, 44) = 0.84$, $\mathrm{MSE} = 1.74$, $p = 0.43$, $\eta_G^2 = 0.04$. Mean RTs in each condition of the three groups are presented in Table 2.

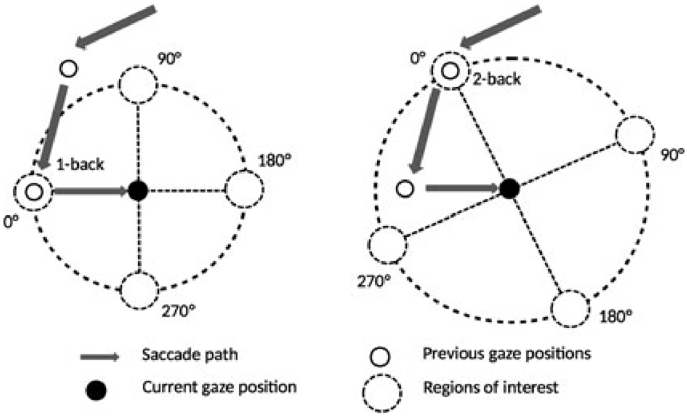

Figure 2. Methods for revealing IOR effects at previous fixations (1-back and 2-back) in the oculomotor search task. We examined the latency (and probability) of saccades landing in a small region (radius = 1°) centred at the 1-back and 2-back fixations and that of those landing in three distance-matched control regions 90°, 180°, and 270° away from the 1-back and 2-back fixations. Saccades landed at the 1-back and 2-back fixations were expected to have longer latencies and lower probabilities than control locations.

Neutral-cue Trials as Baseline

As has been discussed in the Method section, the neutral-cue trials in the cueing task provides an alternative baseline for calculating IOR effect following covert attentional orienting. An ANOVA was performed on the RTs, with variables cueing (valid-cue vs. neutral-cue) and group (CA, DD, vs. RL). The results revealed a main effect of cueing, $F(1, 44) = 6.04$, $MSE = 642$, $p = 0.02$, $\eta_G^2 < 0.01$; RTs were generally longer on valid-cue trials, suggesting an overall IOR effect. The main effect of group was not significant, $F(2, 44) = 0.02$, $MSE = 18777$, $p = 0.98$, $\eta_G^2 < 0.01$, but importantly, the interaction between group and cueing was significant, $F(2, 44) = 3.59$, $MSE = 642$, $p = 0.04$, $\eta_G^2 < 0.01$. The IOR effects observed in the three groups of participants are presented in Figure 3. Previous work has shown that dyslexic children fail to show IOR (Facoetti, Lorusso, *et al.*, 2003). Planned contrasts revealed that, with neutral-cue trials as baseline, statistically reliable IOR effects were observed for the CA group, $t(16) = 1.70$, $p = 0.05$ (1-tailed), Cohen's $d = 0.41$, and the RL group, $t(14) = 3.62$, $p = 0.001$, Cohen's $d = 0.93$, but not for the DD group, $t(14) = 0.58$, $p = 0.71$, Cohen's $d = 0.15$.

Invalid-cue Trials as Baseline

An ANOVA on the RTs, with variables cueing (valid-cue vs. invalid-cue) and group (DD, CA, vs. RL), revealed that the main effect of group was not significant,

Table 2. Mean RTs of each condition in the cueing task. Numbers in the parentheses are SDs

Group	Valid-cue	Invalid-cue	Neutral-cue
CA	525 (24.91)	495 (26.02)	510 (26.57)
RL	532 (24.10)	500 (31.01)	503 (27.80)
DD	508 (25.94)	511 (33.47)	514 (24.52)

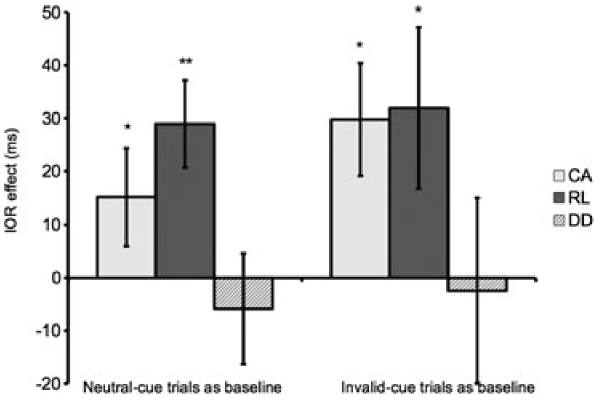

Figure 3. IOR effects in the CA, RL, and DD groups. Error bars denote } ± SEM. * $p \leq 0.05$, ** $p < 0.01$.

$F(2, 44) = 0.02$, MSE = 20876, $p = 0.98$, $\eta_G^2 < 0.01$, nor did its interaction with cueing, $F(2, 44) = 1.85$, MSE = 1528, $p = 0.17$, $\eta_G^2 < 0.01$. However, a significant main effect of cueing was observed, $F(2, 44) = 6.25$, MSE = 1528, $p = 0.02$, $\eta_G^2 < 0.01$. Planned contrasts revealed that, with invalid-cue trials as baseline, significant IOR effects were observed for the CA group, $t(16) = 2.88$, $p = 0.005$ (1-tailed), Cohen's $d = 0.70$, and the RL group, $t(14) = 2.17$, $p = 0.02$, Cohen's $d = 0.56$, but not for the DD group, $t(14) = 0.15$, $p = 0.56$, Cohen's $d = 0.04$. These results replicate the findings of Facoetti, Lorusso, *et al.* (2003).

As clearly shown in Figure 3, IOR was observed in normal developing but not in dyslexic children, regardless of whether neutral- or invalid-cue trials were used as baseline to calculate IOR effects. These consistent findings provide strong evidence that an attentional dysfunction exists in dyslexics. It is important to note that the root of this dysfunction may not be in IOR per se, but rather in a failure or slowness to disengage attention from the cued location (Klein, 2000, 2005). It is possible that dyslexics will show IOR when measures are taken to encourage them to disengage attention from the cued location, for instance, by supplying a second cue at fixation (e.g., MacPherson *et al.*, 2003).

IOR Following Overt Attentional Orienting

On average, 730 (SD = 64), 775 (SD = 110), and 685 (SD = 77) saccades were obtained from each participant of the DD, CA, and RL groups, respectively. A saccade was excluded from the analyses if: (1) it was extremely slow (duration > 100 ms; 8.72%), or (2) it had extremely short (<80 ms; 5.19%) or long (>500 ms; 3.87%) latency. To reveal IOR, we only considered saccades that landed in small regions (diameter = 2°) centred at the 1-back and 2-back fixations, and those centred at distance matched locations 90°, 180°, and 270° away (see Figure 2 for an illustration). After data cleaning, 1845 saccades relative to the 1-back fixation and 1510 saccades relative to the 2-back fixation remained.

Temporal Effect of IOR: Time Taken to Return

In the classic demonstration of IOR following overt orienting (Klein & Macinnes, 1999), IOR was quantified as a temporal delay experienced by saccades directed back to the immediately fixated regions (1-back) and the penultimate (2-back) fixated locations. As clearly shown in Figure 4A, saccades had shorter latencies as their angular distance to the 1-back fixation increased.

An ANOVA on saccade latencies, with variables group (CA, DD, and RL) and angular distance to the 1-back fixation (0°, 90°/270° or 180°), revealed a significant main effect of angular distance, $F(2, 131) = 10.82$, $\text{MSE} = 208289$, $p < 0.001$, $\eta_G^2 = 0.16$. The main effect of group did not reach significance, $F(2, 131) = 0.05$, $\text{MSE} = 208289$, $p = 0.95$, $\eta_G^2 = 0.001$, nor did its interaction with angular distance, $F(4, 131) = 0.58$, $\text{MSE} = 208289$, $p = 0.97$, $\eta_G^2 = 0.007$. Planned contrasts showed that the latency of saccades landing in the 0° location was longer than those landing in the 180° location, $t(40) = 3.79$, $p < 0.001$, Cohen's $d = 0.55$, and the 90/270° location, $t(40) = 3.79$, $p < 0.001$, Cohen's $d = 0.55$. No saccade latency difference was found between the 180° and 90/270° locations, $t(40) = 1.28$, $p = 0.49$, Cohen's $d = 0.19$.

For the analysis of saccades relative to the 2-back fixation, the ANOVA revealed no significant main effect or interaction, all $F < 1$, n.s. (see Figure 4B).

Spatial Effect of IOR: Saccade Landing Probability

One advantage of the oculomotor search task is that it can also reveal the spatial effect of IOR. That is, the effect of IOR in reducing the likelihood of saccades

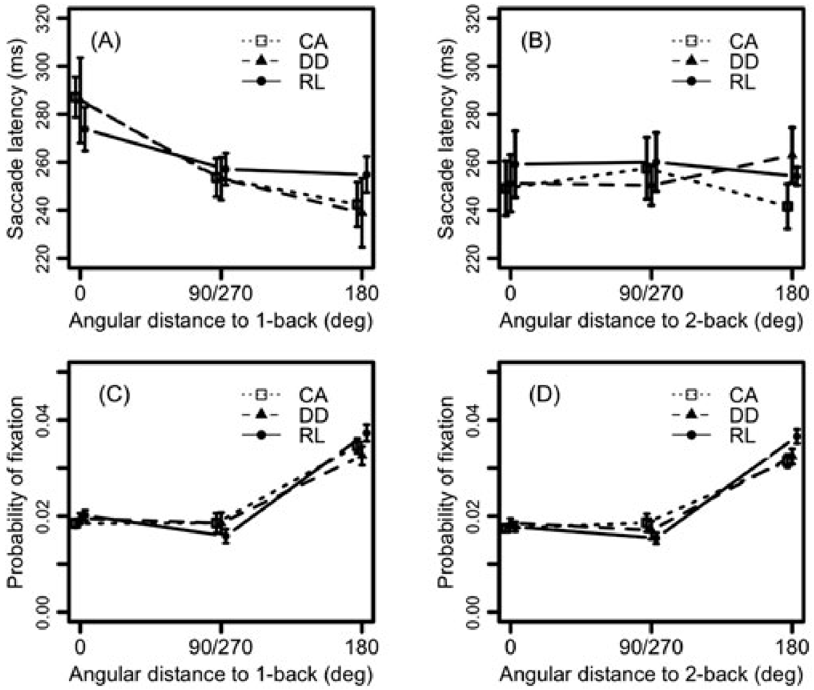

Figure 4. Mean latencies (A–B) and probabilities (C–D) of saccades landing at previous fixations (1-back and 2-back) and distance matched control locations. Error bars denote ± 1 SEM.

returning to previously fixated locations. The probabilities of saccades landing at the 1-back and 2-back fixations, and distance-matched locations are presented in Figure 4C–D.

An ANOVA of saccade landing probabilities, with variables group and angular distance to the 1-back fixation (0°, 90°/270°, and 180°), revealed a significant main effect of angular distance, $F(2, 131) = 74.32$, $\mathrm{MSE} = 9308$, $p < 0.001$, $\eta_G^2 = 0.50$. As is clear from Figure 4C, saccades were less likely to land around the 0° and 90/270° location. The main effect of group and its interaction with angular distance did not reach significance, all $F < 1$, n.s. Planned contrasts revealed that the probability of saccades landing around the 0° and 90/270° locations was lower than that of those landing around the 180° location, all $t > 6.93$, all $p < 0.001$, all Cohen's $d > 1.01$. No difference in saccade landing probability was found between the 0° and 90/270° locations, $t(40) = 0.64$, $p = 0.53$, Cohen's $d = 0.09$.

A similar pattern of results was obtained from the analysis of saccades relative to the 2-back fixation. The main effect of angular distance was significant, $F(2, 131) = 34.15$, $\mathrm{MSE} = 11663$, $p < 0.001$, $\eta_G^2 = 0.46$; saccades were less likely to land around the 0° and 90/270° location. The main effect of group and the two-way interaction between group and angular distance did not reach significance, all $F < 1$, n.s. Planned contrasts also showed lower probability of saccades landing around the 0° and 90/270° location, as compared to the 180° location, all $t > 6.23$, all $p < 0.001$, all Cohen's $d > 0.91$. No difference was found between the 0° and 90/270° locations, $t(40) = 0.33$, $p = 0.87$, Cohen's $d = 0.05$.

One striking observation in the oculomotor search task was that the effect of IOR on saccade latency was limited to the 1-back fixation whereas that on saccade landing probability had no sign of weakening at the 2-back fixation. It remains unclear why the effect of IOR on saccade probability appears to last longer in the present study, but nevertheless, the results presented here clearly show that IOR following overt attentional orienting was normal in dyslexic children. Unlike the cueing task, the oculomotor search task does not entail the possibility of a cue capturing attention and holding it too long. The fact that dyslexic children showed normal IOR in the oculomotor search task further supports the idea that dyslexics may have difficulty in covertly disengaging attention.

DISCUSSION

The present study examined whether IOR—a major driving force of attentional shifts—in tasks that involve covert and overt attentional orienting was abnormal in dyslexic children. More importantly, we tested Chinese dyslexic children, and thus the results also helped to determine whether dyslexics in non-alphabetic writing systems also have dysfunctions in attention.

Selective Impairment of Covert Attentional Shift in Dyslexic Children

Consistent with previous findings (Facoetti *et al.*, 2003), the present experiment found that dyslexic children produced no IOR following covert attentional orienting in a cueing task. More importantly, the present study also revealed an IOR effect in children who were younger than the dyslexic children but had comparable reading ability. These observations suggest that dysfunctions in covert attentional shift may be a causal factor for the reading difficulties encountered by dyslexics (Facoetti *et al*., 2003; Franceschini *et al*., 2013).

Previous studies have shown that dyslexics have poor ability in eye movement control, even in non-reading tasks (Biscaldi *et al*., 2000; Crawford & Higham, 2001), indicating that dyslexics may also have deficits in overt attentional control. Surprisingly, in the oculomotor search task which directly assessed IOR following overt attentional orienting, robust IOR effects were observed not only in typically developing children, but also in children with dyslexia. These results, together with that of the cueing task, suggest that covert attentional shift is selectively impaired in dyslexic children.

Training in attentional orienting has been shown to improve the reading performance of dyslexic children (Facoetti *et al*., 2003; Franceschini *et al*., 2013; Gori *et al*., 2015). For instance, Gori *et al*. (2015) showed that training boosted visual attention in dyslexics, and importantly, the training-induced attentional changes explained a large portion of variance of the reading performance gain in the dyslexics. While it remains unclear why covert attentional shift is selectively impaired in dyslexic children, the important message here is that, for dyslexic children to benefit more from educational activities, educators and parents should consider training programmes specifically targeting at covert attentional shift.

Attentional Dysfunctions and Writing Systems

With a cuing paradigm, Facoetti and colleagues (2003) revealed an attentional dysfunction in Italian dyslexic children (see also Facoetti *et al*., 2000; Facoetti *et al*., 2001). They suggested that the attentional dysfunction may have caused reading difficulty by impacting phonological processes (Facoetti *et al*., 2006; 2010). For alphabetic scripts, phonological decoding is one of the most critical reading skills (Share, 1995; Ziegler & Goswami, 2005). Phonological decoding is based on letter-to-sound conversion, i.e., the mapping of a letter or a grapheme to its corresponding speech-sound. Accurate and rapid attentional shift is needed for segmenting letter strings into its constituent graphemes (Facoetti, *et al*., 2006; 2010). In addition, before the letter-to-sound mapping mechanism is applied, flexible attentional control is needed to filter out irrelevant lateral letters and subsequently to disengage attention from the selected letters. As such, dysfunctions in attentional shift would seriously impair phonological decoding and thus reading (Facoetti *et al*., 2006; 2010; Ruffino *et al*., 2010).

Chinese is a logographic script that is still in use by a large population and it has essentially no letter-to-sound conversion (Perfetti *et al*., 2005; Yeh & Li, 2002). A Chinese character maps onto phonology at the syllable level; it has no part corresponding to phonemes, and thus reading Chinese characters does not depend on the serial letter-to-sound conversion. The present failure to observe IOR in a covert attentional task in Chinese dyslexic children, together with the dysfunctions in covert attention reported in previous studies (Facoetti, *et al*., 2003; 2010; Facoetti *et al*., 2006; Ruffino *et al*., 2010), suggest that the impact of attentional dysfunctions on dyslexia may not be mediated by phonological processes. It is possible that efficient attentional shift is indispensable to rapid and sequential selection of sublexical orthographic units, i.e., letters in alphabetic words or strokes/radicals in Chinese characters (Ruffino *et al*., 2010; see Perry *et al*., 2007, for a computational account). Of course, it is also possible that covert attentional shift is an integral component of all intellectual activities, such as reading, arithmetic, arts, and problem solving. This may explain why attentional dysfunctions have been observed in a large spectrum of learning disorders (Valdois *et al*., 2004; Vidyasagar & Pammer, 2010).

Limitations and Further Study

Before closing our discussion, we would like to note a few limitations of the present work. First, the present study adopted a cross-sectional design to reveal a possible causal link between attentional dysfunction and reading acquisition, a longitudinal study that extends to younger children is needed to confirm our findings. Second, because of the lack of standardized diagnosing tools, it is impossible for us to characterize Chinese dyslexic children in terms of subtypes (Jones *et al*., 2011). Third, given the diversity of literacy and ways of language teaching around the world, more evidence is needed to see if dysfunctions in covert attention are a universal characteristic of DD. Finally, while the present study shows that dyslexic children have selective impairments in covert attentional shift, the neural basis underlying these impairments remains unknown. This issue warrants dedicated exploration in future studies.

CONCLUSION

The present study revealed that Chinese dyslexic children had an IOR deficiency in covert but not in overt attentional tasks. We conclude that covert attentional shift is selectively impaired in dyslexic children. This impairment is not restricted to alphabetic writing systems and it could be a significant contributor to the difficulties encountered by children learning to read.

ENDNOTES

1. For ANOVAs, the effect size measure reported in this paper was generalized eta squared (η_G^2; Olejnik & Algina, 2003). Similar to Cohen's (1988) guideline on eta squared, a η_G^2 of 0.02 could be regarded as small, while one of 0.13 and 0.26 is regarded as medium and large, respectively (Bakeman, 2005).

REFERENCES

American Psychiatric Association (2013). Diagnostic and statistical manual of mental disorders (5th ed. ed.). Washington, D.C: American Psychiatric Publishing.

Backman, J. E., Mamen, M., & Ferguson, H. B. (1984). Reading level design: Conceptual and methodological issues in reading research. *Psychological Bulletin*, *96*(3), 560–568.

Bakeman, R. (2005). Recommended effect size statistics for repeated measures designs. *Behavior Research Methods*, *37*(3), 379–384.

Bavelier, D., Green, C. S., & Seidenberg, M. S. (2013). Cognitive development: Gaming your way out of dyslexia? *Current Biology*, *23*(7), R282–R283.

Biscaldi, M., Fischer, B., & Hartnegg, K. (2000). Voluntary saccadic control in dyslexia. *Perception*, *29* (5), 509–521. doi:10.1068/p2666a.

Bryant, P., & Bradley, L. (1985). Children's reading problems: Psychology and education. Oxford, UK ; New York, NY, USA: Blackwell Publishers.

Bryant, P., & Goswami, U. (1986). Strengths and weaknesses of the reading level design: A comment on Backman, Mamen, and Ferguson. *Psychological Bulletin*, *100*(1), 101–103. doi:10.1037/0033-2909.100.1.101.

Chen, X., & Kao, H. S. (2002). Visual–spatial properties and orthographic processing of Chinese characters. In H.S. Kao, C.K. Leong, D.G. Gao (Ed.), Cognitive Neuroscience Studies of the Chinese Language: Interaction and Reintegration (pp. 175–194). Hong Kong: Hong Kong University Press.

Christie, J., Hilchey, M. D., & Klein, R. M. (2013). Inhibition of return is at the midpoint of simultaneous cues. *Attention, Perception, & Psychophysics*, *75*(8), 1610–1618. doi:10.3758/s13414-013-0510-5.

Cohen, J. (1988). Statistical power analysis for the behavioral sciences (2nd ed.). New York, NY: Routledge Academic.

Crawford, T. J., & Higham, S. (2001). Dyslexia and the centre-of-gravity effect. *Experimental Brain Research*, *137*(1), 122–126. doi:10.1007/s002210000659.

Dukewich, K. R. (2009). Reconceptualizing inhibition of return as habituation of the orienting response. *Psychonomic Bulletin & Review*, *16*(2), 238–251. doi:10.3758/PBR.16.2.238.

Facoetti, A., Corradi, N., Ruffino, M., Gori, S., & Zorzi, M. (2010). Visual spatial attention and speech segmentation are both impaired in preschoolers at familial risk for developmental dyslexia. *Dyslexia*, *16*(3), 226–239. doi:10.1002/dys.413.

Facoetti, A., Lorusso, M. L., Paganoni, P., Cattaneo, C., Galli, R., Umiltà, C., & Mascetti, G. G. (2003). Auditory and visual automatic attention deficits in developmental dyslexia. *Cognitive Brain Research*, *16* (2), 185–191. doi:10.1016/S0926-6410(02)00270-7.

Facoetti, A., Lorusso, M. L., Paganoni, P., Umiltà, C., & Gastone Mascetti, G. (2003). The role of visuospatial attention in developmental dyslexia: Evidence from a rehabilitation study. *Cognitive Brain Research*, *15*(2), 154–164. doi:10.1016/S0926-6410(02)00148-9.

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., Trussardi, A. N., Ruffino, M., Lorusso, M. L., Cattaneo, C., Galli, R., Molteni, M., et al. (2010). Multisensory spatial attention deficits are predictive of phonological decoding skills in developmental dyslexia. *Journal of Cognitive Neuroscience*, *22*(5), 1011–1025. doi:10.1162/jocn.2009.21232.

Facoetti, A., Turatto, M., Lorusso, M. L., & Mascetti, G. G. (2001). Orienting of visual attention in dyslexia: Evidence for asymmetric hemispheric control of attention. *Experimental Brain Research*, *138*(1), 46–53.

Facoetti, A., Zorzi, M., Cestnick, L., Lorusso, M. L., Molteni, M., Paganoni, P., Umiltà, C., et al. (2006). The relationship between visuo-spatial attention and nonword reading in developmental dyslexia. *Cognitive Neuropsychology*, *23*(6), 841–855. doi:10.1080/02643290500483090.

Ferretti, G., Mazzotti, S., & Brizzolara, D. (2008). Visual scanning and reading ability in normal and dyslexic children. *Behavioural Neurology*, *19*(1-2), 87–92.

Fischer, B., Hartnegg, K., & Mokler, A. (2000). Dynamic visual perception of dyslexic children. *Perception*, *29*(5), 523–530. doi:10.1068/p2666b.

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. doi:10.1016/j.cub.2012.03.013.

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. doi:10.1016/j.cub.2013.01.044.

Goswami, U. (2003). Why theories about developmental dyslexia require developmental designs. *Trends in Cognitive Sciences*, *7*(12), 534–540.

Gori, S., Seitz, A. R., Ronconi, L., Franceschini, S., & Facoetti, A. (2015). Multiple causal links between magnocellular–dorsal pathway deficit and developmental dyslexia. *Cerebral Cortex*Online First. doi:10.1093/cercor/bhv206.

Handford, M. (1987). *Wheres Waldo?*. New York: Little, Brown and Company.

Hari, R., & Renvall, H. (2001). Impaired processing of rapid stimulus sequences in dyslexia. *Trends in Cognitive Sciences*, *5*(12), 525–532. doi:10.1016/S1364-6613(00)01801-5.

Hilchey, M. D., Hashish, M., MacLean, G. H., Satel, J., Ivanoff, J., & Klein, R. M. (2014). On the role of eye movement monitoring on inhibition of return in a go/no-go task. *Vision Research*, *96*, 133–139.

Ho, C. S.-H., Chan, D. W.-O., Lee, S.-H., Tsang, S.-M., & Luan, V. H. (2004). Cognitive profiling and preliminary subtyping in Chinese developmental dyslexia. *Cognition*, *91*(1), 43–75. doi:10.1016/S0010-0277(03)00163-X.

Jones, K., Castles, A., & Kohnen, S. (2011). Subtypes of developmental reading disorders: Recent developments and directions for treatment. *ACQ: issues in language, speech and hearing*, *13*(2), 79–83.

Jonides, J., & Mack, R. (1984). On the cost and benefit of cost and benefit. *Psychological Bulletin*, *96*(1), 29–44. doi:10.1037/0033-2909.96.1.29.

Klein, R. (1988). Inhibitory tagging system facilitates visual search. *Nature*, *334*(6181), 430–431. doi:10.1038/334430a0.

Klein, R. (2000). Inhibition of return. *Trends in Cognitive Sciences*, *4*(4), 138–147. doi:10.1016/S1364-6613(00)01452-2.

Klein, R., Kingstone, A., & Pontefract, A. (1992). Orienting of visual attention. In K. Rayner (Ed.), Eye movements and visual cognition: Scene perception and reading (pp. 46–65). New York: Springer-Verlag.

Klein, R. M., Christie, J., & Morris, E. P. (2005). Vector averaging of inhibition of return. *Psychonomic Bulletin & Review*, *12*(2), 295–300.

Klein, R. M. (2005). On the role of endogenous orienting in the inhibitory aftermath of exogenous orienting. In U. Mayr, E. Awh, & S. Keele (Eds.), Developing individuality in the human brain: A tribute to Michael I. Posner (pp. 45–64). Washington, DC: American Psychological Association.

Klein, R. M., & Macinnes, J. W. (1999). Inhibition of return is a foraging facilitator in visual search. *Psychological Science*, *10*(4), 346–352. doi:10.1111/1467-9280.00166.

Koch, C., & Ullman, S. (1985). Shifts in selective visual attention: Towards the underlying neural circuitry. *Human Neurobiology*, *4*(4), 219–227.

Krause, M. B. (2015). Pay attention!: Sluggish multisensory attentional shifting as a core deficit in developmental dyslexia. *Dyslexia*, *21*(4), 285–303. doi:10.1002/dys.1505.

Leck, K. J., Weekes, B. S., & Chen, M. J. (1995). Visual and phonological pathways to the lexicon: Evidence from Chinese readers. *Memory & Cognition*, *23*(4), 468–476.

Lei, L., Pan, J., Liu, H., McBride-Chang, C., Li, H., Zhang, Y., Chen, L., et al. (2011). Developmental trajectories of reading development and impairment from ages 3 to 8 years in Chinese children. *Journal of Child Psychology and Psychiatry, and Allied Disciplines*, *52*(2), 212–220. doi:10.1111/j.1469-7610.2010.02311.x.

Li, D., & Chen, G. (1989). Combined Raven's test (CRT): Chinese revised version. In Shanghai: East China Normal University. Shanghai: East China Normal University.

Li, H., Shu, H., McBride-Chang, C., Liu, H. Y., & Xue, J. (2009). Paired associate learning in Chinese children with dyslexia. *Journal of Experimental Child Psychology*, *103*(2), 135–151. doi:10.1016/j.jecp.2009.02.001.

MacPherson, A. C., Klein, R. M., & Moore, C. (2003). Inhibition of return in children and adolescents. *Journal of Experimental Child Psychology*, *85*(4), 337–351. doi:10.1016/S0022-0965(03)00104-8.

Olejnik, S., & Algina, J. (2003). Generalized eta and omega squared statistics: Measures of effect size for some common research designs. *Psychological Methods*, *8*(4), 434–447. doi:10.1037/1082-989X.8.4.434.

Patel, S. S., Peng, X., & Sereno, A. B. (2010). Shape effects on reflexive spatial selective attention and a plausible neurophysiological model. *Vision Research*, *50*(13), 1235–1248. doi:10.1016/j.visres.2010.04.010.

Perfetti, C. A., Liu, Y., & Tan, L. H. (2005). The lexical constituency model: Some implications of research on Chinese for general theories of reading. *Psychological Review*, *112*(1), 43–59. doi:10.1037/0033-295X.112.1.43.

Perry, C., Ziegler, J. C., & Zorzi, M. (2007). Nested incremental modeling in the development of computational theories: The CDP+ model of reading aloud. *Psychological Review*, *114*(2), 273–315. doi:10.1037/0033-295X.114.2.273.

Plaza, M., & Cohen, H. (2007). The contribution of phonological awareness and visual attention in early reading and spelling. *Dyslexia*, *13*(1), 67–76. doi:10.1002/dys.330.

Posner, M. I. (1980). Orienting of attention. *The Quarterly Journal of Experimental Psychology*, *32*(1), 3–25.

Posner, M. I., & Cohen, Y. (1984). Components of visual orienting. In H. Bouma, & D. G. Bouwhuis (Eds.), Attention and performance X: Control of language processes (pp. 531–556), *10*. Hillsdale, NJ: Erlbaum.

Richlan, F. (2014). Functional neuroanatomy of developmental dyslexia: The role of orthographic depth. *Frontiers in Human Neuroscience*, *8*, 347. doi:10.3389/fnhum.2014.00347.

Roach, N. W., & Hogben, J. H. (2008). Spatial cueing deficits in dyslexia reflect generalised difficulties with attentional selection. *Vision Research*, *48*(2), 193–207. doi:10.1016/j.visres.2007.11.001.

Ruffino, M., Trussardi, A. N., Gori, S., Finzi, A., Giovagnoli, S., Menghini, D., Benassi, M., et al. (2010). Attentional engagement deficits in dyslexic children. *Neuropsychologia*, *48*(13), 3793–3801. doi:10.1016/j.neuropsychologia.2010.09.002.

Satel, J., Wang, Z., Trappenberg, T. P., & Klein, R. M. (2011). Modeling inhibition of return as short-term depression of early sensory input to the superior colliculus. *Vision Research*, *51*(9), 987–996. doi:10.1016/j.visres.2011.02.013.

Van Selst, M., & Jolicoeur, P. (1994). A solution to the effect of sample size on outlier elimination. *The Quarterly Journal of Experimental Psychology Section A. Human Experimental Psychology*, *47*(3), 631–650. doi:10.1080/14640749408401131.

Share, D. L. (1995). Phonological recoding and self-teaching: Sine qua non of reading acquisition. *Cognition*, *55*(2), 151–218 discussion 219–226.

Shaywitz, S. E., & Shaywitz, B. A. (2005). Dyslexia (specific reading disability). *Biological Psychiatry*, *57* (11), 1301–1309. doi:10.1016/j.biopsych.2005.01.043.

Shu, H., Chen, X., Anderson, R. C., Wu, N., & Xuan, Y. (2003). Properties of school Chinese: Implications for learning to read. *Child Development*, *74*(1), 27–47. doi:10.1111/1467-8624.00519.

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. doi:10.1037/0022-0663.98.1.122.

Smith, T. J., & Henderson, J. M. (2011). Does oculomotor inhibition of return influence fixation probability during scene search? *Attention, Perception, & Psychophysics*, *73*(8), 2384–2398. doi:10.3758/s13414-011-0191-x.

Snowling, M. J. (2000). Dyslexia (2ndVol. xiv ed.). Malden: Blackwell Publishing.

Thomas, L., Ambinder, M., Hsieh, B., Levinthal, B., Crowell, J., Irwin, D., Kramer, A., et al. (2006). Fruitful visual search: Inhibition of return in a virtual foraging task. *Psychonomic Bulletin & Review*, *13*(5), 891–895.

Valdois, S., Bosse, M.-L., & Tainturier, M.-J. (2004). The cognitive deficits responsible for developmental dyslexia: Review of evidence for a selective visual attentional disorder. *Dyslexia*, *10* (4), 339–363. doi:10.1002/dys.284.

Vellutino, F. R., Fletcher, J. M., Snowling, M. J., & Scanlon, D. M. (2004). Specific reading disability (dyslexia): What have we learned in the past four decades? *Journal of Child Psychology and Psychiatry*, *45*(1), 2–40. doi:10.1046/j.0021-9630.2003.00305.x.

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. doi:10.1016/j.tics.2009.12.003.

Wang, L.-C., & Yang, H.-M. (2011). The comparison of the visuo-spatial abilities of dyslexic and normal students in Taiwan and Hong Kong. *Research in Developmental Disabilities*, *32*(3), 1052–1057. doi:10.1016/j.ridd.2011.01.028.

Wang, Z., & Klein, R. M. (2010). Searching for inhibition of return in visual search: A review. *Vision Research*, *50*(2), 220–228. doi:10.1016/j.visres.2009.11.013.

Weger, U. W., & Inhoff, A. W. (2006). Attention and eye movements in reading inhibition of return predicts the size of regressive saccades. *Psychological Science*, *17*(3), 187–191. doi:10.1111/j.1467-9280.2006.01683.x.

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.

Zhang, Y., Zhang, L., Shu, H., Xi, J., Wu, H., Zhang, Y., & Li, P. (2012). Universality of categorical perception deficit in developmental dyslexia: An investigation of Mandarin Chinese tones. *Journal of Child Psychology and Psychiatry, and Allied Disciplines*, *53*(8), 874–882. doi:10.1111/j.1469-7610.2012.02528.

Zhou, Y., McBride-Chang, C., & Wong, N. (2014). What is the role of visual skills in learning to read? *Frontiers in Psychology*, *5*. doi:10.3389/fpsyg.2014.00776.

Ziegler, J. C., & Goswami, U. (2005). Reading acquisition, developmental dyslexia, and skilled reading across languages: A psycholinguistic grain size theory. *Psychological Bulletin*, *131*(1), 3–29. doi:10.1037/0033-2909.131.1.3.