Dyslexic children are sluggish in disengaging spatial attention

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Previous work has shown that inefficient attentional orienting is likely a causal factor for dyslexia; however, the nature of this attentional dysfunction remains unclear. The process of attentional orienting is characterized by an early facilitation effect, resulting from the successful engagement of attention, and a later inhibitory effect—frequently referred to as inhibition of return (IOR)—which encourages attentional disengagement and facilitates efficient visual sampling. The present study examined the time course of attentional orienting in dyslexic and typically developing children, by parametrically manipulating the cue-target onset asynchronies in a spatial cueing task. Experiment 1 revealed an early facilitation effect in dyslexic children, suggesting that they have no issue in engaging attention to salient spatial locations. However, contrast to both age-matched and reading level-matched healthy controls, no reliable IOR effect was observed in dyslexic children, suggesting that they have difficulties in disengaging attention. When a second cue was presented to encourage attentional disengagement in Experiment 2, reliable IOR effects were observed in the same group of dyslexic children, and importantly, the onset time of IOR was comparable with that in healthy controls. These results clearly show a selective impairment of attentional disengagement in dyslexic children and provide a solid empirical basis for intervention programmes focusing on attentional shifting.

KEYWORDS
developmental dyslexia, inhibition of return, Posner cueing task, spatial attention
Dyslexia is a severe reading deficit that inflicts about 5–9% of the population (American Psychiatric Association, 2013; Shaywitz & Shaywitz, 2005). Despite decades of research, a fundamental understanding of the mechanisms underlying dyslexia is still lacking. Whereas deficits in phonological processing have long been suggested as a good predictor of dyslexia (e.g., Goswami, 2002; Ramus, 2003; Snowling, 2000), an increasing number of studies show that the dysfunction in attentional orienting is also a primary contributor (e.g., Krause, 2015; Valdois, Bosse, & Tainturier, 2004; Vidyasagar & Pammer, 2010; Zhou, McBride-Chang, & Wong, 2014; but see Skottun & Skoyles, 2006). For instance, it has been shown that attention is impaired not only in dyslexic children (e.g., Facoetti et al., 2010; Lallier et al., 2010) but also in children with familial risk of developmental dyslexia (Facoetti, Corradi, Ruffino, Gori, & Zorzi, 2010). Researchers have also shown that the efficiency of attentional orienting is a good predictor of reading ability (Ferretti, Mazzotti, & Brizzolara, 2008; Franceschini, Gori, Ruffino, Pedrolli, & Facocetti, 2012; Plaza & Cohen, 2007; Ruffino, Gori, Boccardi, Molteni, & Facocetti, 2014), and more importantly, intervention programmes focusing on attentional orienting have proven effective in improving the reading performance of dyslexic children (e.g., Facoetti, Lorusso, Paganoni, Umiltà, & Gastone Mascetti, 2003; Franceschini et al., 2013; Franceschini, Trevisan, et al., 2017; Franceschini, Bertoni, Gianesini, Gori, & Facocetti, 2017).

During reading, attention is quickly shifted along the lines of text to allow accurate targeting of rapid eye movements, which bring the most sensitive part of the retina to words or letters for detailed processing. It is no surprise that researchers have long argued that the reading difficulties of dyslexic children may arise from inefficient attentional orienting, that is, the sluggish attentional shifting theory (for a review, see Hari & Renvall, 2001). The most convincing evidence for this theory comes from attentional blink studies that require subjects to identify two targets in a rapid serial visual presentation (RSVP) stream (Duncan, Ward, & Shapiro, 1994). The accuracy of identifying a second target (T2) that immediately follows the correct identification of the first target (T1) is typically low but quickly recovers to about 75% at a 540-ms T1–T2 SOA. T2 identification accuracy in dyslexics also recovers, however, at a much longer (700 ms) T1–T2 stimulus onset asynchrony (SOA) (Facoetti, Ruffino, Peru, Paganoni, & Chelazzi, 2008; for similar findings, see also Hari & Renvall, 2001; Hari, Valta, & Uutela, 1999; for contradicting findings, see McLean, Castles, Coltheart, & Stuart, 2010). In addition to the slow recovery, the attentional blink effect is stronger in dyslexic children, with the accuracy of identifying T2 (given T1 is correctly identified) being at least one standard deviation below that of normal developing children (Facoetti et al., 2008). These findings suggest that dyslexics have difficulties in attentional control. However, the nature of this attentional dysfunction is not well understood. Importantly, these studies do not tell us much about the orienting of attention in the spatial domain, which is more relevant to reading.

Frequently examined in a spatial cueing task (Posner, 1980), the orienting of attention in the spatial domain is characterized by an early facilitation effect due to attentional capture or engagement and a later inhibitory aftereffect, which encourages attentional disengagement and orienting towards novel locations (e.g., Koch & Ullman, 1985). The later inhibitory aftereffect, widely known as inhibition of return (IOR), is indispensable to visual sampling as it discourages perseverative orienting towards previously attended locations (e.g., Klein, 1988; for a review, see Wang & Klein, 2010). Compared with healthy controls, the early facilitation effect is generally weaker in dyslexic children (e.g., Facoetti et al., 2008; Ruffino et al., 2010). The IOR effect, on the other hand, was absent in dyslexic children in studies that examined this effect (Ding et al., 2016; Facoetti, Lorusso, Paganoni, Cattaneo, et al., 2003; Franceschini et al., 2018). The absence of IOR in dyslexic children could be that the early facilitation was too weak to give rise to any IOR, or the onset of IOR is delayed because it takes longer for dyslexic children to disengage attention from the currently attended location. This issue can be further clarified by examining the time course of attentional orienting to reveal at what time the early facilitation turns into IOR. To this end, the present study adopted the classic Posner cueing task (Posner & Cohen, 1984), in which a target that requires a detection response is preceded by an uninformative peripheral cue. The cue-target onset asynchrony (CTOA) was parametrically manipulated to reveal both early facilitation and later IOR effects.

To briefly anticipate the findings, Experiment 1 revealed a robust facilitation effect in dyslexic children at a short CTOA, suggesting that dyslexic children have no trouble in engaging attention to salient location. However, contrast...
to age- and reading level-matched controls, no reliable IOR effect was observed in dyslexic children, suggesting a deficit in disengaging attention. Experiment 2 provided further evidence to this conclusion by showing that a second (central) cue, known to facilitate attentional disengagement (e.g., Briand, Larrison, & Sereno, 2000; MacPherson, Klein, & Moore, 2003; Pratt & Fischer, 2002), helped dyslexic children to produce robust IOR at a short CTOA that is comparable with healthy controls.

2 | EXPERIMENT 1: THE TIME COURSE OF ATTENTIONAL ORIENTING

The primary purpose of the Experiment 1 was to map out the time course of attentional orienting in dyslexic children and healthy controls with a spatial cueing task.

2.1 | Method

The research protocol reported here was approved by a local institutional review board, and written informed consent was obtained from the parents of all children who participated in the present experiments.

2.1.1 | Participants

Two hundred and twenty-four third-grade children from a local elementary school were screened for dyslexia with the Hong Kong behaviour checklist for primary students (BCL-P; Chan, Ho, Tsang, Lee, & Chung, 2004), a Chinese Character recognition test (Shu, Chen, Anderson, Wu, & Xuan, 2003), and the standard combined Raven's test (CRT; Li & Chen, 1989). Detailed information about these tools are presented in the next section. The dyslexic children were identified with the following criteria: (a) being rated at high risk for dyslexia on the BCL-P questionnaire by their teachers; (b) scored below the 10th percentile on the Chinese character recognition test (more stringent than other Chinese dyslexia studies); (c) had normal non-verbal IQ (>85); and (d) had normal or corrected-to-normal visual acuity and no known ADHD symptoms. Twenty-three children met these criteria, but five quit during testing and three was unable to complete the experimental task, which involved the use of an eye tracker.

Twenty children on the same grade were selected as chronological age-matched controls (CA), one of them quit early during testing. In addition, 20 first-grade children who had the same reading level as the third-grade dyslexic children were selected as reading level-matched controls (RL); two of them quit during testing. This group of younger controls is indispensable in a reading-level matched design (e.g., Backman, Mamen, & Ferguson, 1984; Goswami, 2003), which helps to determine whether an attentional deficit, if were observed in the dyslexic children, is likely a causal factor for dyslexia, as has been suggested in previous work (e.g., Ding et al., 2016; Facoetti, Trussardi, et al., 2010; Franceschini et al., 2012). Specifically, if deficits in attentional orienting is causing dyslexia rather than the other way around, we expect to observe attentional deficits in the DD group but not in the RL group. The sample size was determined based on several recent studies examining visuospatial attention in dyslexic children (e.g., Ding et al., 2016; Franceschini et al., 2012).

The results presented here are based on 15 dyslexic children (DD; six boys and nine girls, age range: 8.5–9.5 years), 19 age-matched controls (CA; 9 boys and 10 girls, age range: 8.5–9.5 years), and 18 reading level-matched controls (RL; 10 boys and 8 girls, age range: 6.5–7.5 years). All children were native Mandarin speakers. The CRT and character recognition scores and the BCL-P ratings are presented in Table 1. The non-verbal IQ of the DD group was lower than that of the CA group, \( t(32) = 3.19, p = 0.007, \text{Cohen's } d = 1.38 \), and the RL group, \( t(31) = 5.42, p < 0.001, \text{Cohen's } d = 2.25 \), but was in the normal range. The RL group performed as good as the DD group on the Chinese character recognition test, \( t(31) = 0.70, p = 0.58, \text{Cohen's } d = 0.63 \); the CA group made significantly less errors than the DD group, \( t(32) = 34.14, p < 0.001, \text{Cohen's } d = 15.21 \), and the RL group, \( t(35) = 14.98, p < 0.001, \text{Cohen's } d = 16.08 \)
On the BCL-P questionnaire, the rating was higher for the DD group than for the CA group, $t(32) = 6.33$, $p < 0.001$, Cohen's $d = 2.59$, and the RL group, $t(31) = 7.44$, $p < 0.001$, Cohen's $d = 3.58$.

### 2.1.2 Screening tools

#### The BCL-P questionnaire

Dyslexic children may not show all of their reading problems in a testing setting. As teachers interact with children on a daily basis, they have the opportunity to observe different aspects of children's reading behaviours and can give a comprehensive evaluation of children's reading ability (Sattler, 2008). The BCL-P questionnaire was developed by researchers in Hong Kong to assess the daily reading performance of students. We used this questionnaire as a complementary tool for screening dyslexic children because it correlates well with clinical diagnosis (Chan et al., 2004). The teachers of the students were asked to rate the frequency of 34 reading-related behaviours on a 5-point Likert scale, ranging from 1 (never observed) to 5 (frequently observed). Students who score 18 points or above on this questionnaire are at high risk for dyslexia.

#### The Chinese character recognition test

No standardized tool is available in mainland China for clinical diagnosis of dyslexia. The most widely used tool in dyslexia research is a Chinese character recognition test developed by Shu et al. (2003). This test requires the child to read out a list of Chinese characters, which are presented in increasing difficulty. The maximum possible score on this test is 150. In previous studies, children who scored one standard deviation below the grade average were regarded as having severe reading difficulties and possibly dyslexic (e.g., Ding et al., 2016; Ho, Chan, Lee, Tsang, & Luan, 2004; Li, Shu, McBride-Chang, Liu, & Xue, 2009; Wang & Yang, 2011; Zhang et al., 2012). A more stringent criterion (i.e., the lowest 10%) was used in the present study.

#### The standard CRT

The standard CRT (Li & Chen, 1989) was used to assess the non-verbal intelligence of the children.

### 2.1.3 Apparatus and stimuli

The spatial cueing task (Posner & Cohen, 1984) was adopted to examine the time course of attentional orienting. This task was tested in a dimly lit room, and stimuli were presented on a 19-inch CRT monitor, at a viewing distance of 62 cm (maintained with a chinrest). Stimulus presentation and data registration were controlled by a Windows 7 PC, running custom scripts written in Python. Eye movements were monitored with an EyeLink® 1000 eye tracker (SR Research, Ottawa, Canada). The tracking accuracy of this eye tracker was reported to be 0.2° or better, and the participant's gaze position was sampled at 1,000 Hz.

Three grey boxes (Weber contrast = 83.88) that subtended 1.8° visual angle were used as placeholders in the cueing task (see Figure 1). The peripheral boxes flanked a grey central fixation cross (Weber contrast = 83.88),

### TABLE 1 The scores on the CRT test, the Chinese character recognition test, and the BCL-P questionnaire

<table>
<thead>
<tr>
<th>Group</th>
<th>Age (years)</th>
<th>CRT</th>
<th>BCL-P</th>
<th>Character recognition error</th>
</tr>
</thead>
<tbody>
<tr>
<td>CA</td>
<td>9.08 (0.12)</td>
<td>115.72 (2.71)</td>
<td>5.22 (1.51)</td>
<td>23.78 (0.90)</td>
</tr>
<tr>
<td>RL</td>
<td>7.17 (0.11)</td>
<td>123.45 (2.60)</td>
<td>3.06 (1.25)</td>
<td>86.89 (4.25)</td>
</tr>
<tr>
<td>DD</td>
<td>8.90 (0.12)</td>
<td>104.67 (2.15)</td>
<td>22.07 (2.37)</td>
<td>83.00 (1.60)</td>
</tr>
</tbody>
</table>

Note. Scores on the character recognition task denote the number of misnamed Chinese characters. On the BCL-P questionnaire, a higher score means more problematic reading behaviours. Numbers in the parentheses are standard errors of the mean. BCL-P: behaviour checklist for primary students; CRT: combined Raven's test.
and their distance to the central fixation was 9°. In the cueing task, the participant is required to respond to a target stimulus that is preceded by an uninformative peripheral cue. In the present study, the cue was implemented as the brightening and thickening of one of the peripheral boxes (Weber contrast = 740.86). The target was a bright disk (diameter = 1°, Weber contrast = 740.86), which always appeared in the peripheral boxes against a black background (0.43 cd/m²).

### 2.1.4 Task procedure

The sequence of events in a single trial is illustrated in Figure 1. Each trial started with a drift check (controlled by the experimenter) to ensure the participant was fixating at the centre of the display. Successful drift check was followed by the presentation of three grey placeholder boxes and a central fixation cross. One thousand milliseconds later, the cue was presented at the left or right box for 100 ms; the target was presented immediately (0 ms gap), or 100, 300, or 700 ms later (randomly intermixed within block of trials). The target appeared in one of the peripheral placeholder boxes, and the participant had 1,500 ms to respond with the space bar on a standard QWERTY keyboard. The target was not presented on 25% of the trials to discourage anticipatory responses. When the target was presented, it appeared in the cued box on half of the trials and in the box opposite to the cue on the remaining trials. We will follow the convention of previous studies and refer to these two types of trials as "validly cued” and “invalidly cued,” respectively.

The cueing task was tested with four blocks of 40 trials. A standard 9-point calibration of the eye tracker was performed at the beginning of each block, or whenever a break was required by the participant. The participants were reminded to maintain fixation if the fixation was broken on two consecutive trials.

### 2.1.5 Data analysis

In cueing tasks, attentional orienting is characterized by an early facilitation effect (i.e., shorter RTs for validly cued targets) and a later inhibitory effect (longer RTs for validly cued targets, i.e., IOR). In the present study, the primary dependent measure of interest is RT, or more specifically the RT difference between validly cued and invalidly cued targets.

### 2.2 Results

To discourage anticipatory responses, 25% of the trials were catch trials. The false alarm rates for the CA, DD, and RL groups were 2.30%, 2.29%, and 2.95%, respectively; no difference was found between the three groups, \( F(2, 49) = 0.20, p = 0.82, \eta_p^2 = 0.01 \). The miss rates for the CA, DD, and RL groups were 1.19%, 1.77%, and 1.95%, respectively; again, no difference was found between the three groups, \( F(2, 49) = 0.64, p = 0.53, \eta_p^2 = 0.03 \). The active engagement of the oculomotor system may invoke untoward motoric effects (e.g., Hilchey, Klein, & Satel, 2014), so trials during which eye movements occurred were excluded from the analysis. These trials accounted
for 20.49%, 19.46%, and 23.61% of the trials (including catch trials) for the CA, DD, and RL groups, respectively. Analysis revealed that the amount of trials excluded did not differ across the three groups, $F(2, 49) = 0.51$, $p = 0.61$, $\eta^2_p = 0.02$.

The RTs from the noncatch trials were cleaned based on the number of trials in each experimental cell of each participant, following the criteria given in Van Selst and Jolicoeur (1994, Table 4). This outlier removal procedure effectively controls for the impact of the number of successfully completed trials in different experimental cells. It has been widely adopted by researchers in the field, with various automated tools (e.g., R packages) freely available online. This procedure excluded only a small portion of the trials, 3.00%, 1.99%, and 2.52% for the CA, DD, and RL groups, respectively.

Mean RTs of all conditions in the CA, DD, and RL groups are presented in Figure 2. An ANOVA on the RTs, with variables group (DD, CA, and RL), cueing (validly vs. invalidly cued), and CTOA (100, 200, 400, and 800 ms),
revealed a significant main effect of CTOA, $F(3, 147) = 16.28$, $p < 0.001$, $\eta_p^2 = 0.25$, with the RTs generally decreases as the CTOA increases. This effect was observed, most likely because the expectation for the onset of the target strengthens as the CTOA increases, that is, the foreperiod effect (Niemi & Naatanen, 1981). The main effect of cueing did not reach significance, $F(1, 49) = 0.49$, $p = 0.490$, $\eta_p^2 = 0.01$; however, significant two-way interactions were observed between cueing and CTOA, $F(3, 147) = 12.46$, $p < 0.001$, $\eta_p^2 = 0.20$, and between cueing and group, $F(2, 49) = 5.85$, $p = 0.005$, $\eta_p^2 = 0.19$. The interaction between cueing and CTOA is not unexpected as in cueing tasks the initial facilitation effect will turn into IOR as the CTOA increases. The interaction between cueing and group occurred because the overall cueing effect was more positive in the CA and RL groups than that in the DD group (see Figure 2). A marginal three-way interaction was also observed, $F(6, 147) = 2.01$, $p = 0.068$, $\eta_p^2 = 0.08$; this effect was mainly driven by the IOR effect at the 400-ms CTOA in the RL group (see Figure 2). Because the non-verbal IQ of the DD group was lower than that of the other two groups, an ANCOVA on the RTs, with the non-verbal IQ as a covariate, was also performed. The overall pattern of the results was the same as that reported here.

For the CA group, the prototypical time course of attentional orienting was observed. Planned contrasts (two-tailed) revealed facilitation effects for the 100-ms CTOA, $t(18) = 1.93$, $p = 0.070$, $dz = 0.44$, and the 200-ms CTOA, $t(18) = 2.26$, $p = 0.037$, $dz = 0.52$. IOR effects (i.e., slower responses to validly cued targets) were observed for the 400-ms CTOA, $t(18) = 2.63$, $p = 0.017$, $dz = 0.60$, and the 800-ms CTOA, $t(18) = 2.86$, $p = 0.010$, $dz = 0.66$. For the DD group a strong facilitation effect was observed for the 100-ms CTOA, $t(14) = 2.60$, $p = 0.021$, $dz = 0.67$, but the IOR effect did not show up even for the longest CTOA (800 ms), all $t < 1.55$ and $p > 0.142$. For the RL group, no reliable facilitation effect was observed at the short CTOAs (<400 ms), all $t < 0.78$ and $p > 0.444$, but a significant IOR effect was observed at the 400-ms CTOA, $t(17) = 3.61$, $p = 0.002$, $dz = 0.85$. The IOR effect for the 800-ms CTOA approached marginal significance, $t(17) = 1.73$, $p = 0.101$, $dz = 0.41$. The failure to observe IOR effect in dyslexic children was consistent with the findings of previous studies (Ding et al., 2016; Facoetti, Lorusso, Paganoni, Cattaneo, et al., 2003).

A careful examination of Figure 2 revealed a global shift of the cueing effects between the DD, CA, and RL groups. Three ANOVAs were performed on the RTs, each comparing two of the three groups. For the ANOVA comparing the RL and CA groups, the two-way interaction between cueing and group was not significant, $F(1, 35) = 2.065$, $p = 0.160$, $\eta_p^2 = 0.048$, nor did the three-way interaction, $F(3, 105) = 1.170$, $p = 0.325$, $\eta_p^2 = 0.025$. So although the IOR effect for the 400-ms CTOA in the RL group appears to be stronger than that in the CA group, overall, the time course of the cueing effect was similar across these two groups. For the ANOVA comparing the CA and DD groups, the two-way interaction between cueing and group was significant, $F(1, 32) = 4.916$, $p = 0.034$, $\eta_p^2 = 0.130$; the three-way interaction was not significant, $F(3, 96) = 1.597$, $p = 0.195$, $\eta_p^2 = 0.036$. As shown in Figure 2, the cueing effects were overall more "positive" (leaning towards IOR) in the CA group. For the ANOVA comparing the RL and DD groups, both the two-way interaction, $F(1, 31) = 10.447$, $p = 0.003$, $\eta_p^2 = 0.251$, and the three-way interaction were significant, $F(3, 93) = 2.968$, $p = 0.036$, $\eta_p^2 = 0.074$. Nevertheless, same as in the CA group, overall, more positive cueing effects were observed in the RL group. The overall pattern of results is best summarized in Figure 3: The cueing effect was negative for short CTOAs and positive for longer CTOAs for all three groups; however, compared with the CA and RL groups, the cueing effects in the DD group were more negative (i.e., leaning towards facilitation), with the overall cueing effects being 5.87 (SD = 55.19), 21.38 (SD = 81.37), and −17.64 ms (SD = 70.94) for the CA, RL, and DD groups, respectively.

Overall, the results of Experiment 1 clearly show that dyslexic children’s capacity in orienting attention towards salient locations is intact (see Section 4 for detailed discussion), if not superior than healthy controls, and their attentional deficits are rooted in an inferior inhibitory mechanism (i.e., IOR), which is vital for disengaging attention. To verify this conclusion, the same group of dyslexic children were tested in a second experiment, in which a second cue was presented at fixation. The second cue will automatically capture attention and thus facilitates the disengagement of attention from the validly cued location (e.g., Briand et al., 2000; MacPherson et al., 2003; Pratt & Fischer, 2002).
3 | EXPERIMENT 2: FACILITATING ATTENTIONAL DISENGAGEMENT WITH A SECOND CUE

3.1 | Method

3.1.1 | Participants

The dyslexic children tested in Experiment 1 all took part in Experiment 2.

3.1.2 | Apparatus, stimuli, and task procedure

The apparatus and stimuli were the same as Experiment 1. The task procedure was the same as Experiment 1, except that a second cue that lasted for 100 ms was presented at the central box immediately following the first cue, and consequently, the 100-ms CTOA was not tested.

3.2 | Results and discussion

The false alarm rate and miss rate in Experiment 2 were 4.82% and 1.81%, respectively. Eye movements were detected on 12.81% of the trials (including catch trials). As in Experiment 1, these trials were excluded from analysis.

The RTs were cleaned with the same protocol as Experiment 1: this removed only 3.19% of the noncatch trials. Mean RTs in all conditions are presented in Figure 4 (left panel). An ANOVA on the RTs revealed significant main effects for cueing (validly vs. invalidly cued), $F(1, 14) = 20.11, p = 0.001, \eta_p^2 = 0.59$, and CTOA (200, 400, and 800 ms), $F(2, 28) = 9.69, p = 0.001, \eta_p^2 = 0.41$. The RTs were generally longer for validly cued targets and decreased as the CTOA increased. The two-way interaction was marginal, $F(2, 28) = 2.69, p = 0.085, \eta_p^2 = 0.16$. Planned contrasts revealed a significant IOR effects for the 400-ms CTOA, $t(14) = 3.22, p = 0.006$ (two tailed), $dz = 0.83$, and the 800-ms CTOA, $t(14) = 3.38, p = 0.021$ (two tailed), $dz = 0.87$. 

**FIGURE 3** An illustration summarizing the main findings of Experiment 1. The cueing effects were more positive (i.e., leaning towards inhibition) in the RL and CA groups compared with those in the DD group, suggesting a clear deficit in inhibitory control in dyslexic children. CTOA: cue-target onset asynchrony; IOR: inhibition of return [Colour figure can be viewed at wileyonlinelibrary.com]
As noted above, the most important methodological change in Experiment 2 was the addition of a second cue. Previous studies have demonstrated that a second cue will facilitate the disengagement of attention from the cued location and thus facilitates the onset of IOR (e.g., Briand et al., 2000; MacPherson et al., 2003; Pratt & Fischer, 2002). We compared the cueing effects (the RT difference between validly and invalidly cued targets) in the dyslexic children between Experiments 1 (without second cue) and 2 (with second cue). An ANOVA on the cueing effects, with variables CTOA (200, 400, and 800 ms) and second cue (with vs. without), revealed significant main effects for CTOA, $F(2, 28) = 3.79, p = 0.035, \eta^2_p = 0.21,$ and second cue, $F(1, 14) = 8.64, p = 0.011, \eta^2_p = 0.38.$ The interaction between CTOA and second cue was not significant, $F(2, 28) = 0.83, p = 0.46, \eta^2_p = 0.06.$ As clearly shown in Figure 4 (right panel), an overall more positive cueing effect was observed in Experiment 2 (with second cue). When the second cue was presented to encourage attentional disengagement, the onset time of IOR was comparable with that of the age- and reading level-matched controls (at the 400-ms CTOA), providing further evidence that attentional disengagement is impaired in dyslexic children.

**FIGURE 4** Mean RTs (ms) in Experiment 2, and the cueing effects observed in the DD group in Experiments 2 (with second cue) and 1 (no second cue). Error bars denote ±standard error of the mean. **p < 0.01. CTOA: cue-target onset asynchrony [Colour figure can be viewed at wileyonlinelibrary.com]**

As noted above, the most important methodological change in Experiment 2 was the addition of a second cue. Previous studies have demonstrated that a second cue will facilitate the disengagement of attention from the cued location and thus facilitates the onset of IOR (e.g., Briand et al., 2000; MacPherson et al., 2003; Pratt & Fischer, 2002). We compared the cueing effects (the RT difference between validly and invalidly cued targets) in the dyslexic children between Experiments 1 (without second cue) and 2 (with second cue). An ANOVA on the cueing effects, with variables CTOA (200, 400, and 800 ms) and second cue (with vs. without), revealed significant main effects for CTOA, $F(2, 28) = 3.79, p = 0.035, \eta^2_p = 0.21,$ and second cue, $F(1, 14) = 8.64, p = 0.011, \eta^2_p = 0.38.$ The interaction between CTOA and second cue was not significant, $F(2, 28) = 0.83, p = 0.46, \eta^2_p = 0.06.$ As clearly shown in Figure 4 (right panel), an overall more positive cueing effect was observed in Experiment 2 (with second cue). When the second cue was presented to encourage attentional disengagement, the onset time of IOR was comparable with that of the age- and reading level-matched controls (at the 400-ms CTOA), providing further evidence that attentional disengagement is impaired in dyslexic children.

4 | GENERAL DISCUSSION

The dysfunction in attentional orienting is likely a causal factor for the reading difficulties experienced by dyslexics (e.g., Ding et al., 2016; Facoetti, Lorusso, Paganoni, Umiltà, & Gastone Mascetti, 2003; Franceschini et al., 2012). To reveal the nature of the attentional dysfunction in dyslexics, the present study examined the time course of attentional orienting in both dyslexic children and healthy controls with a spatial cueing task. The participants responded to a visual target that was preceded by an uninformative peripheral cue. In age-matched healthy controls IOR effects were observed to follow early facilitation effects, that is, the prototypical behavioural effects produced by attentional orienting. The dyslexic children also produced a robust facilitation effect, suggesting that they have no trouble in engaging attention to salient locations. However, they produced no reliable IOR effect, even for the longest CTOA examined in the present study (800 ms). Comparing the pattern of cueing effects between the dyslexic children and healthy controls revealed that the cueing effects in dyslexic children were generally more negative (i.e., leaning towards facilitation) than that in healthy controls, suggesting a deficit in inhibitory control, which may result in slow disengagement of attention. This conclusion was further supported by a second experiment showing that a second cue—known to automatically draw attention away and thus facilitates attentional disengagement (e.g., MacPherson et al., 2003; Moores, Cassim, & Talcott, 2011; Moores, Tsouknida, & Romani, 2015)—helped dyslexic children to produce IOR effects as early as healthy controls. These results provide clear evidence that dyslexic children are sluggish in attentional disengagement, and this dysfunction is rooted in deficits in inhibitory control (see Facoetti, Lorusso, Paganoni, Umiltà, et al., 2003; Klein & D’Entremont, 1999, for similar conclusions).
4.1 | Deficits in attentional engagement or disengagement

Previous studies have employed a variety of tasks to reveal possible attentional deficits in dyslexics (for reviews, see Cassim, Talcott, & Moores, 2014; Hari & Renvall, 2001; Krause, 2015). The present study opted to use the spatial cueing task to examine the time course of attentional orienting, that is, the early facilitation effect due to attentional engagement and subsequent inhibition (IOR), which encourages orienting towards novel locations. The results of Experiment 1 replicated the finding that dyslexic children show no (or very weak) IOR in spatial cueing tasks (e.g., Ding et al., 2016; Facoetti, Lorusso, Paganoni, Cattaneo, et al., 2003). The observation of a strong early facilitation effect in dyslexic children, however, contradicts the popular notion that dyslexic children are less efficient in engaging attention (e.g., Facoetti, Lorusso, Cattaneo, Galli, & Molteni, 2005; Ruffino et al., 2010). For example, an early study by Brannan and Williams (1987) found that, in contrast to good readers, poor readers produced no attentional facilitation. Facoetti, Turatto, Lorusso, and Mascetti (2001) also failed to observe attentional facilitation in dyslexic children in a cueing task with informative peripheral cues (valid on 80% of the trials). In a subsequent study, Facoetti et al. (2003) revealed that dyslexic children do show attentional facilitation, but only at a longer CTOA (400 ms) compared with healthy controls (for similar findings, see Facoetti et al., 2005). Importantly, recent studies showed that this deficit in attentional engagement appears to exist in dyslexics with phonological decoding problems but not in dyslexics with near-normal phonological skills (Facoetti, Trussardi, et al., 2010; Ruffino et al., 2010).

Phonological decoding is widely regarded as one of the most critical reading-related cognitive components in alphabetic languages (Share, 1995; Ziegler & Goswami, 2005). Flexible attentional control is crucial for phonological decoding, as it helps to filter out irrelevant lateral letters and subsequently disengages attention from the selected letters, so letter strings can be processed in units of graphemes (Facoetti et al., 2006). Chinese is a logographic script, which has essentially no letter-to-sound conversion, that is, no need for phonological decoding (e.g., Perfetti, Liu, & Tan, 2005; Yeh & Li, 2002). A Chinese character maps onto phonology at the syllable level, and it has no part corresponding to phonemes in alphabetic scripts. The failure to observe IOR in both Chinese (the present study and Ding et al., 2016) and Italian (Facoetti, et al., 2003) dyslexic children suggests an IOR deficit that is not specific to a writing system. The observation of strong attentional facilitation in Chinese dyslexic children (see Figure 2), however, suggests that the absence of IOR in Chinese dyslexic children may have a different origin. It is possible that the lack of IOR in dyslexic children learning alphabetic scripts arises as a result of weak (or no) attentional engagement in the first place, whereas the lack of IOR in Chinese dyslexic children arises as the result of too strong attentional engagement, which takes longer time to dissipate. This speculation warrants further empirical exploration, for instance, with cross-culture studies comparing the time course of attentional orienting in Chinese and Western dyslexic children. Regardless of the nature of the attentional dysfunction lies in attentional engagement or disengagement, the deficit in IOR have been observed in dyslexic children across different writing systems. An IOR deficit will lead to less efficient visual sampling (e.g., Klein, 1988; Klein & MacInnes, 1999) and slow down the letter-to-sound conversion in alphabetic scripts or the sequential selection of sublexical orthographic units in Chinese.

Training programmes focusing on attentional orienting have been shown to improve the reading performance of dyslexic children (e.g., Facoetti, Lorusso, Paganoni, Umiltà, et al., 2003; Franceschini et al., 2013). For instance, visual hemisphere specific stimulation training, which encourages rapid endogenous attentional orienting by presenting briefly flashed words in the peripheral visual fields, significantly improves dyslexic children’s reading efficiency (Facoetti, Lorusso, Paganoni, Umiltà, et al., 2003). Franceschini et al. (2013) also found that playing action video games improves children’s attentional skills and reading performance. The most important finding of the present study is that the attentional deficits in dyslexic children are rooted in insufficient inhibitory control (IOR). We believe training programmes targeting at inhibitory control are likely more effective in alleviating the reading difficulties experienced by dyslexic children.
4.2 IOR effects in young children

Previous cross-sectional studies of attentional orienting have failed to observe IOR effects in young children. For instance, Brodeur and Enns (1997) tested children in the age range of 6–10 years, as well as young and old adults; they observed no IOR effect in young children and old adults, though significant overall effects of facilitation were observed. MacPherson et al. (2003) examined attentional orienting in young children in a similar age range (5–10 years); no IOR effect was observed unless a second cue was used. These findings seem to contradict the present observation of IOR in the healthy controls, who were in roughly the same age range.

It is worth noting that developmental studies have reported IOR effects in infants as young as 6 months (Clohessy, Posner, Rothbart, & Vecera, 1991; Varga, Frick, Kapa, & Dengler, 2010), and recent studies have reported IOR effects in young children in the same age range as the present study (Ding et al., 2016) and in slightly older children (9–13 years; Facoetti, Lorusso, Paganoni, Cattaneo, et al., 2003). Thus, the present observation of IOR effects in the young children was not unconventional. The discrepancy here is likely the result of methodological differences across studies. Notably, the task of Brodeur and Enns (1997) required discrimination responses and that of MacPherson et al. (2003) required spatial localization responses. The present study, however, required a simple detection response instead (as in Posner and Cohen's seminal IOR study). It is known that discrimination tasks delay the onset of IOR (e.g., Lupiáñez, Milán, Tornay, Madrid, & Tudela, 1997), and more generally, the appearance time of IOR increases linearly with task difficulty (for a graphical review of existing evidence, see Klein, 2000). It is possible that the longest CTOAs tested by MacPherson et al. (800 ms) and Brodeur and Enns (450 ms) were too short to reveal IOR effects in their relatively more difficult tasks.

Methodological differences aside, a delay in the onset of IOR may also be the result of “a weakness in strategic control of attention, such that the endogenous removal of attention from the validly cued location is typically less efficient” (MacPherson et al., 2003, p. 348). Although remotely likely, we cannot rule out the possibility that the executive functions of the Chinese children (i.e., the subjects of the present study and Ding et al., 2016) may have matured earlier than those tested in MacPherson et al. (2003). It is known that East Asian children perform better than Western children on various measures of executive functions (e.g., Oh & Lewis, 2008; Sabbagh, Xu, Carlson, Moses, & Lee, 2006), possibly because impulse control is more highly valued in both family and school settings in East Asian cultures.

4.3 Limitations of the present study

Before closing our discussion, we would like to note a few limitations of the present work. First, the dyslexic children had lower non-verbal IQ than the healthy controls, although the non-verbal IQ of the dyslexic children was all in the normal range. Without a standardized diagnosis tool, we had to screen dyslexia based on the reading ability of a rather small population (i.e., students from the same school), making it difficult to perfectly match the non-verbal IQ between dyslexic children and healthy controls. Second, for exactly the same reason, it is rather difficult for us to further increase the sample size, which will require coordinated screening of students from multiple schools. Third, no healthy control but only dyslexic children were examined in Experiment 2. It remains unclear whether the second cue also facilitates the onset of IOR in healthy controls. Nevertheless, this less than optimal experimental design does not undermine the main conclusion of the present study in any way.

AUTHOR CONTRIBUTIONS

J. Z., Z. W., Y. D., and W. F. designed the experiments. W. F. collected the data. W. F., J. Z., and Z. W. analysed the data. W. F. drafted the manuscript, and J. Z. and Z. W. provided critical revisions. All the authors approved the final version of the manuscript for submission.
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