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Received: 4 April 2023 | Revised: 30 August 2023 | Accepted: 23 October 2023

DOI: 10.1111/desc.13458

Developmental Science WILEY

RESEARCH ARTICLE

Children with dyslexia show no deficit in exogenous spatial attention but show differences in visual encoding

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Funding information
Stanford Maternal and Child Health Institute (MCHRI); NIH NICHD, Grant/Award Number: R01-HD09586101

Abstract

In the search for mechanisms that contribute to dyslexia, the term "attention" has been invoked to explain performance in a variety of tasks, creating confusion since all tasks do, indeed, demand "attention." Many studies lack an experimental manipulation of attention that would be necessary to determine its influence on task performance. Nonetheless, an emerging view is that children with dyslexia have an impairment in the exogenous (automatic/reflexive) orienting of spatial attention. Here we investigated the link between exogenous attention and reading ability by presenting exogenous spatial cues in the multi-letter processing task—a task relevant for reading. The task was gamified and administered online to a large sample of children ($N = 187$) between 6 and 17 years. Children with dyslexia performed worse overall at rapidly recognizing and reporting strings of letters. However, we found no evidence for a difference in the utilization of exogenous spatial cues, resolving two decades of ambiguity in the field. Previous studies that claimed otherwise may have failed to distinguish attention effects from overall task performance or found spurious group differences in small samples.

KEYWORDS
dyslexia, exogenous attention, reading, spatial attention, visual encoding

Research Highlights

- We manipulated exogenous visual spatial attention using pre-cues in a task that is relevant for reading and we see robust task effects of exogenous attention.
- We found no evidence for a deficit in utilizing exogenous spatial pre-cues in children with dyslexia.
- However, children with dyslexia showed reduced recognition ability for all letter positions.
- Children with dyslexia were just as likely to make letter transposition errors as typical readers.

1 | INTRODUCTION

In the last two decades there has been growing interest in the notion that visual spatial attention underlies developmental dyslexia, a reading disability that affects 5%–20% of the global population (Wagner et al., 2020). Two prominent lines of research contribute to the interest. First, many studies use the "visual attention span" task: participants are asked to identify as many stimuli as they can from a set that is flashed briefly. Performance in this task has been shown to predict reading ability above and beyond other known correlates of reading development, like phonological awareness (Bosse et al., 2007; Lallier et al., 2013; Lobier et al., 2012; Prado et al., 2007). However, the "visual attention span" task does not involve an experimental manipulation of attention. When attention is not manipulated orthogonal to the task it leads to circular explanation. For instance, the outcome measure of the visual attention span task—which is the number of encoded and reported items—is both an explican and an explicandum. Performance differences, thus, may also be due to other non-attentional processes (like rapid visual encoding, recognition, memory, etc.).

Secondly, some studies have experimentally manipulated visual spatial attention using spatial pre-cues. A pre-cue is a stimulus that appears just before a target display and may or may not indicate the location of the target stimulus. There are two mechanisms of attentional deployment: endogenous, in which resources are voluntarily directed to a certain location and is based on current goals; or exogenous, in which a sudden onset of a peripheral stimulus involuntarily captures attention (Carrasco, 2011). Uninformative, brief (typically ~100–120 ms), peripheral spatial cues tap into the reflexive/automatic/exogenous orientation of attentional resources whereas informative, longer (typically ~300–500 ms), central spatial cues tap into endogenous/volitional control of attentional resources. Thus, depending on how the pre-cues are designed, they inform us about different mechanisms of visual spatial attention. Typically, performance is improved when the cue "validly" indicates the target location, compared to when the cue is absent, neutral, or invalid.

Some studies have suggested that people with dyslexia have a deficit in exogenous orienting of attention, albeit in visual detection and discrimination tasks that are not directly related to reading. Facoetti et al. (2000) used a simple dot detection task with peripheral, 80% valid, pre-cues to probe exogenous orienting and reported that participants with dyslexia showed no reaction time advantage (a faster response). On replacing peripheral cues with central cues, they reported no group difference between the Control and the Dyslexia groups, suggesting a deficit in the exogenous orienting of attention and not the endogenous system. A number of other studies that followed have reported differences between Dyslexia and Control groups in utilizing peripheral cues (Facoetti et al., 2000, 2003, 2008; Franceschini et al., 2012), but with ambiguity on whether the deficit is in the utilization of valid cues (facilitation) or in the suppression of invalid cues (inhibition). For instance, Facoetti et al. reported that children with dyslexia showed no benefit for valid exogenous spatial cues and concluded that there is a deficit in exogenous attentional engagement (Facoetti et al., 2000). In later studies, they reported a deficit specific to inhibiting invalid exogenous spatial cues, and concluded there is a deficit in disengagement, not engagement, of exogenous spatial attention (Facoetti et al., 2006, 2010; Franceschini et al., 2012, 2013). It is evident that even within the same laboratory there are inconsistent results, perhaps because sample sizes are generally small, and tasks are not designed to clearly isolate the role of a specific attentional system in reading. For example, classic findings implicating exogenous attention in dyslexia had sample sizes ranging from $n = 10$ (Facoetti et al., 2006), $n = 22$ (Facoetti et al., 2010), $n = 14$ (Franceschini et al., 2012), and $n = 20$ (Franceschini et al., 2013). Despite the limitations, the interpretation that poor readers shift spatial attention more slowly than skilled readers fits the "sluggish attention shift hypothesis"—purported to explain various deficits reported in children with dyslexia across the visual and auditory domains when processing rapidly presented information (Facoetti et al., 2000, 2003, 2006, 2008, Riitta Hari & Renvall, 2001).

In the present study, we manipulated exogenous attention in a task relevant for reading in children (6–17 years) to test the hypothesis that children with dyslexia have a deficit in exogenous spatial attention. We made the experiment accessible to children by "gamifying" it and deploying it on an online platform.

2 | RESULTS

2.1 | Overall accuracy in the multi-letter processing task predicts reading skill

The multi-element processing task (Hawelka & Wimmer, 2005) measures the amount of information that can be extracted from brief visual displays (Averbach, 1968; Sperling, 1960). In the whole report version, participants report the identity of as many letters as possible from a briefly displayed string. In the partial report version, which we used, the task is to report one of the letters at a post-cued location after the stimulus disappears. We used letters as stimuli, because word recognition is limited by the ability to identify its component letters, and our goal is to examine how exogenous spatial attention affects processing combinations of letters (Pelli et al., 2003).

Figure 1 shows an example trial sequence. In our task, we used all uppercase consonants that do not form real words. This ensures that accurate recognition must be done for each letter independently. We manipulated exogenous attention by presenting spatial pre-cues just before the string of letters. Valid and invalid exogenous pre-cues were three red lines that flashed briefly (50 ms) below the letter locations. The pre-cue is valid if it appeared on the same side as the post-cued letter, and invalid if on the opposite side of the post-cued position. Neutral pre-cues flashed under all 6 letter positions at once. Valid, invalid, and neutral pre-cues were equally likely, meaning that the cue was uninformative for the task. The neutral condition provides a baseline measure of how well a participant can encode a string of letters. To assess the temporal dynamics of exogenous attention, we also varied the time between the pre-cues and the letters, which is referred to as the cue-target onset asynchrony (CTOA). On half of the trials the CTOA was

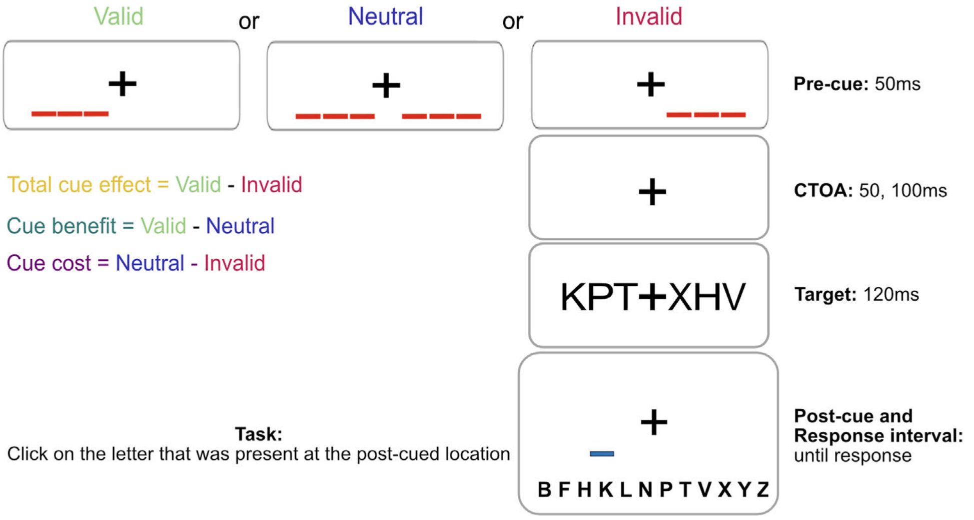

FIGURE 1 Manipulating exogenous spatial attention in a task relevant for attention. Trial sequence: On each trial the participant is presented with a briefly flashed string of 6 letters, three to the left and three to the right of fixation. Each letter spanned 0.5° of visual angle with 0.58° center-to-center spacing. The eccentricities of the inner, middle, and outer letters on each side were 0.58°, 1.16°, and 1.74°, respectively. Immediately after the letters disappear, a "post-cue" appears: a blue line under one of the letter locations. The participant's task is to report the identity of the target letter at the post-cue location by clicking on one of 12 letters presented choices below the post-cue (note that 6 of the 12 letter choices are part of the target string and 6 are not part of the target string).

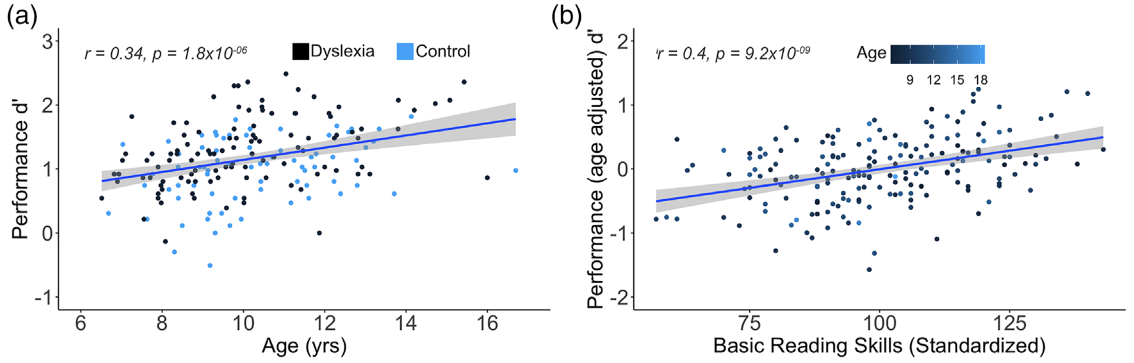

FIGURE 2 Overall accuracy in the multi-letter processing task predicts reading skill. (a) Correlation between task performance and age. (b) Correlation between age-adjusted task performance and basic reading ability (Woodcock Johnson Basic Reading Score; WJ-BRS). See also Figure S1.

50 ms, and on the other half it was 100 ms. In adults, the total cue effects peaks at 50 ms and drops significantly at 100 ms (Ramamurthy et al., 2021). We observed that children between 6 and 17 years of age show higher performance in the valid trials compared to neutral and invalid trials, across both CTOAs (see Figure 3b) [Mean accuracy: Valid trials: 40.945% ± 1.262 (SEM); Neutral: 37.148% ± 1.191; Invalid: 28.137% ± 1.031]. We observed no significant difference between the CTOAs in all aspects of exogenous attentional effects (see Figure S2). Therefore, for all other analysis that follows, effects across both CTOA trials were averaged.

Averaging performance in the neutral condition across both CTOAs, we found that accuracy (*d'*) improved with age [Pearson's $r = 0.34$; $p = 1.8 \times 10^{-06;}$ Figure 2a]. We then used linear regression to remove the effect of age on task performance. The residuals from this model reflect an age-standardized measure of task performance. We observed a moderate and highly significant correlation between reading ability (measured with the Woodcock Johnson Basic Reading Skills Index WJ-BRS (Woodcock, 2011)) and age-standardized task performance [$n = 187$, $r = 0.42$; $p = 9.2 \times 10^{-09}$; Figure 2b]. Results were comparable when the TOWRE (Tarar et al., 2015) [$n = 187$, $r = 0.36$; $p = 3.9 \times 10^{-07}$; see Figure S1b] or the ROAR: Rapid Online Assessment of Reading (Yeatman et al., 2020) were used as an index of reading ability [$n = 64$; $r = 0.38$; $p = 0.0019$, see Figure S1b]. Further, in a subset of children with IQ scores, we found that age and IQ adjusted task performance correlated with reading ability [$n = 129$, $r = 0.26$, $p = 0.0035$]. These findings show that the ability to rapidly encode multiple letters from a brief display is related to reading development.

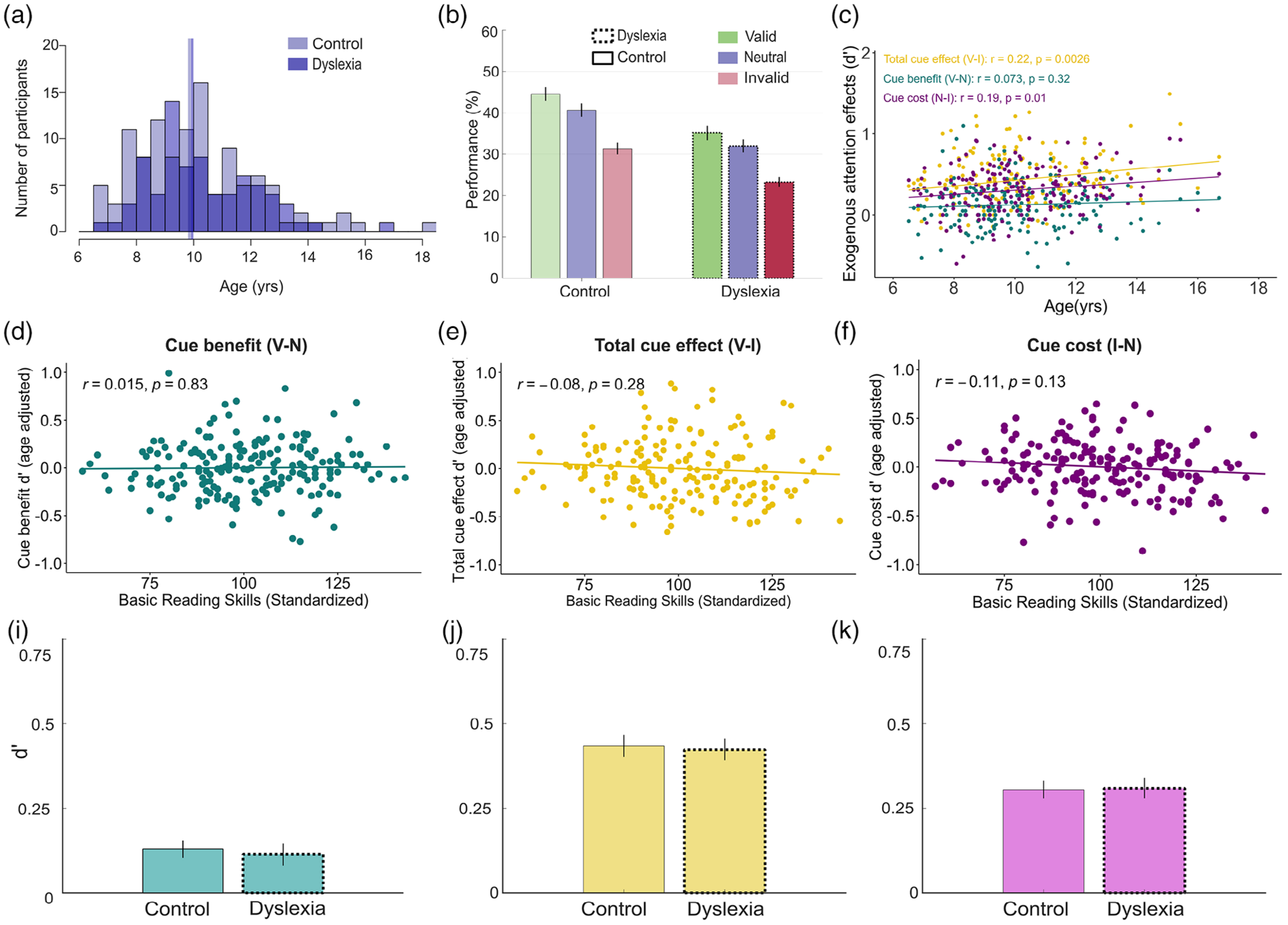

FIGURE 3 No evidence for a deficit in utilizing exogenous spatial pre-cues in children with dyslexia. (a) Age distribution of the participants included in the analysis; (b) Performance in the multi-letter processing task across all trial types and both CTOAs for the control and the children with dyslexia groups, respectively; (c) Exogenous attentional effects (d') as a function of age; (d–f) Correlation between basic reading ability (Woodcock Johnson basic reading scores) and attention effects, namely cue benefits, total cue effects and cue cost; (i–k) The cue benefit (i), total cue effect (j), and cue cost (k) are equivalent for the Control (solid line) and Dyslexia (dotted line) groups, respectively. Data are represented as mean ± SEM. See also Figures S2 and S5.

2.2 | Exogenous attention develops with age but is not correlated with reading ability

The exogenous cue *benefit* is measured by taking the difference in performance between valid and neutral cue conditions (valid—neutral), and the cue *cost* by taking the difference in performance between neutral and invalid trials (neutral—invalid). The *total cue effect* is the difference in performance in the valid and invalid trial conditions (valid—invalid). We see that, overall, exogenous total cue effects and cue cost develop with age [correlation coefficients $r = 0.22$; $p = 0.0026$ and $r = 0.19$; $p = 0.01$], however, exogenous cue benefits show no relationship with age [$r = 0.073$, $p = 0.32$; Figure 3c]. This is consistent with previous theories that show target facilitation (indexed by the cue benefit) and distractor suppression (inverse of the cue cost) operate under distinct mechanisms (Noonan et al., 2016).

We used linear regression to remove the effect of age on cue effects; the residuals from this model reflect an age-standardized measure of exogenous attention. We observe no correlation between age-standardized exogenous total cue effects and basic reading ability [cue benefit: $r = 0.015$, $p = 0.833$; total cue effect: $r = -0.079$, $p = 0.278$; cue cost: $r = -0.111$, $p = 0.131$; see Figure 3d–f], showing that the effects of exogenous cues are unrelated to individual differences in reading development.

2.3 | No evidence for a deficit in utilizing exogenous spatial pre-cues in children with dyslexia

In the previous section, we treated reading ability as a continuous predictor of task performance. We now do a group analysis, comparing children with dyslexia (from now on simply referred to as the Dyslexia group) to children without dyslexia (referred to as the Control group). The Dyslexia group was defined as any child with a standardized reading score <1 SD in Woodcock Johnson Basic Reading Skills composite

TABLE 1 Summaries all the statistical tests for the comparison of the Control and the Dyslexia groups in terms of the magnitude of cueing effects on accuracy.

	Cue benefits (V–N)	Total cue effects (V–I)	Cue cost (V–I)
t-test	$t(185) = 0.369, p = 0.713$	$t(185) = 0.229, p = 0.819$	$t(185) = 0.102, p = 0.919$
Bayes Factor	0.165 ± 0.06	0.165 ± 0.06	0.162 ± 0.06
TOST	$t(165.76) = 3.482, p = 0.00038$; Equivalence bounds of −0.150 and 0.150	$t(184.38) = 3.465, p = 0.00033$; Equivalence bounds of −0.171 and 0.171	$t(174.77) = 3.576, p = 0.00023$; Equivalence bounds of −0.145 and 0.145

index and/or the TOWRE index. Fifty of the seventy-five children in the Dyslexia group also had a clinical diagnosis of dyslexia. The age distributions across the Dyslexia and Controls were similar: median ±SD ages = 9.945 ± 1.845 and 9.8 ± 2.173, respectively (see Figure 3a). If children with dyslexia have a deficit in utilizing exogenous cues, we predict smaller cue benefits and costs compared to the Control group. We compared cue benefits, total cue effects and cue cost between Dyslexia and Control groups with independent samples t-tests and found no significant group differences (see Table 1 first row). We next calculated the Bayes Factor (*BF*) which indicates the relative strength of evidence for two hypotheses: a BF greater than one indicates increasing evidence for the alternate (group differences) over null (no group differences) hypothesis; values less than 1 indicate evidence for the null hypothesis. A BF close to one means that data does not favor either hypothesis over the other (computed using the Bayes Factor package in R (Rouder et al., 2012). The BF indicated substantial evidence for an absence of a group difference in exogenous attention between the two groups (see second row in Table 1). These values (1/3 to 1/10) are considered moderate to strong evidence in favor of the null hypothesis (Jeffreys, 1998; Lee & Wagenmakers, 2014). We also performed the "two one sided tests" (TOST, computed using the TOST package in R) (Lakens et al., 2018) procedure that tests whether the group difference and the confidence interval of the group difference fall within the equivalence interval. The equivalence interval is set to effect size calculated based on sample size of both groups with significance level set to 0.05 and power to 0.95. The TOST test shows that exogenous attentional effects in the Control and Dyslexia groups were equivalent (Table 1). In summary, across all the three statistical tests, we show that there are no differences between the Control and Dyslexia groups in how they utilize exogenous attentional cues (see Figure 3i–k).

2.4 | Children with dyslexia show reduced recognition ability for all letter positions

Though there were no group differences in exogenous attention effects, overall accuracy in the multi-letter processing task (neutral cue trials) is significantly higher for the Control group compared to the Dyslexia group [Cohen's d: 0.578; $t(185) = 3.846$, $p = 0.000165$] (see Figures 4a and 3b). So, we next asked if groups differ in letter recognition accuracy, specific to different letter positions in the string. Many studies have shown that letter recognition accuracy differs across positions within a string (Castet et al., 2017; Mason, 1982; Tydgat & Grainger, 2009). The profile is W-shaped (Grainger et al., 2016; Ramamurthy et al., 2021; Scaltritti et al., 2018; Tydgat & Grainger, 2009), with greater accuracy for outermost positions and those closest to fovea, and diminished accuracy for internal letters.

Consistent with the literature, we found that children, overall, show a W-shaped profile like adults (Ramamurthy et al., 2021). A LME was fit to performance (d') with letter position (1–6) and groups (Control and Dyslexia) as fixed effects. We see a significant main effect of letter position [F (5, 1128) = 119.15; $p = 2.796 \times 10^{-101}$] and group [$F(1,1128) = 19.694$; $p = 9.9802 \times 10^{-06}$] and no significant interaction [$F(5,1128) = 0.853$; $p = 0.512$]. Thus, the W-shaped function is the same shape for both the groups, with the Dyslexia group showing an overall lower accuracy compared to that of the Control group (Figure 4b). Letter positions were further classified into outer (1, 6), middle (2, 5), and inner (3, 4) positions, respectively. A LME was fit to accuracy (d') data with letter grouping (outer, middle, and inner) and groups as fixed factors. We see a significant main effect of group [$F(1,564) = 13.105$; $p = 0.00032$] and letter grouping [$F(2,564) = 286.26$; $p = 1.5437 \times 10^{-86}$] but no significant interaction [$F(2,564) = 1.349$; $p = 0.2604$]. Figure 4c shows that both groups show substantially worse performance in identifying the crowded (middle) letter positions compared to the outermost and the innermost letters. In fact, d' was below *0* for the middle letters, which suggests that when the middle position was post-cued, participants systematically reported a letter from a different position or misidentified the target letter.

2.5 | Children with dyslexia are just as likely to make letter transposition errors as typical readers

To correctly recognize the target letter, both position and identification of the target letter within the string is critical. Some studies, with a small number of participants, have suggested letter position specific deficits in dyslexia and have categorized such individuals as developmental letter position dyslexics (Friedmann et al., 2012; Friedmann & Rahamim, 2007). To understand the type of errors children make while recognizing letters within a string we categorized each incorrect trial into two error types. A transposition error is when the participant confuses the relative position and reports another letter in the string instead of the target letter. For example, in a string "K N B T Y P," reporting K, N, B, T, or P for the post-cued target Y would be classified as a transposition error. A transposition error is thus due to incorrect

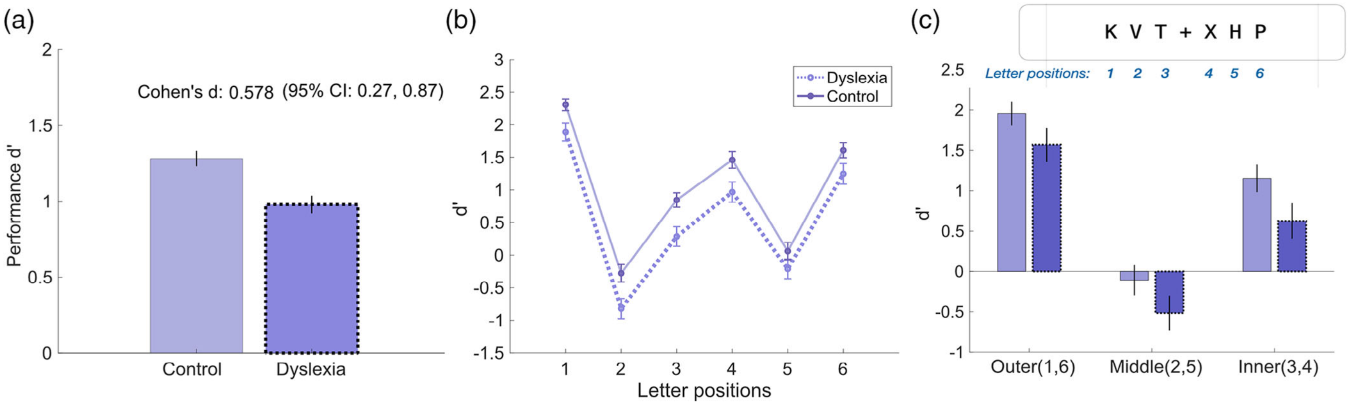

FIGURE 4 Children with dyslexia show reduced recognition ability for all letter positions. (a) Group differences in performance in the multi-letter processing task; (b) Serial position function for letter recognition is W-shaped across both groups; (c) Letter recognition varies drastically for the outer, middle and inner positions with lowest recognition ability for the middle letters across both groups. Data are represented as mean ± SEM.

position encoding. A misidentification error is when the participant reports a letter that was not present in the string. For example, in the same target string, a misidentification error would be reporting V instead of the target Y. We first see that transposition errors were not correlated with misidentification errors ($r = 0.054$, $p = 0.46$; see Figure 5a), showing that errors due to position encoding are unrelated to errors due to misidentification.

We computed the proportions of both error types as the number of errors divided by the total number of trials, separately for each group. The results are shown in Figure 5b. In general, transposition errors were 2x more frequent than misidentification errors, similar to neurotypical adults (Ramamurthy et al., 2021). A LME fit on proportion errors with error type (transposition and misidentification) and groups as fixed factors shows a significant main effect of groups [$F(1,370) = 14.627$; $p = 0.000154$], error type [$F(1,370) = 365.91$; $p = 3.337 \times 10^{-57}$] and no interaction between error type and groups [$F(1,370 = .124$; $p = 0.725$]. Thus, poor readers make more errors overall, but are not more likely to make any specific type of error.

Errors specific to letter position: In previous studies with this task transposition errors were common for the middle letters (positions 2 and 5). This could be due to crowding (Ramamurthy et al., 2021). Some studies have suggested visual crowding as a potential cause of dyslexia mainly based on data showing that dyslexic individuals experience elevated crowding compared to the typical population (Bouma & Legein, 1977; Joo et al., 2018; Martelli et al., 2009). Based on the above theory, we might hypothesize that transposition errors vary as a function of different letter positions and interact differently across the two groups. To test this hypothesis, we split the transposition errors based on letter grouping (outer, middle and inner). We observed that transposition errors (Figure 5c) and misidentification errors (Figure 5d) vary across letter grouping. An LME fit to errors with letter grouping (outer, inner, and middle), error type (transposition and misidentification) and group as fixed factors, showed main effects of group [$F(1,1110) = 16.096$, $p = 0.642 \times 10^{-05}$], letter grouping [$F(2,1110) = 351.5$, $p = 5.536 \times 10^{-119}$] and error type [$F(1,1110) = 535.56$, $p = 5.268 \times 10^{-97}$]. There was no significant three-way interaction [$F(2,1110) = 0.646$, $p = 0.524$]. There was, however, a significant two-way interaction between letter grouping and error types [$F(2,1110) = 225.4$, $p = 7.046 \times 10^{-83}$] showing that across different letter groupings, error types vary (see Figure 5c,d). We saw no significant two-way interaction between group and error types [$F(1,1110) = 0.059$, $p = 0.808$] nor a two-way interaction between group and letter grouping [$F(2,1110) = 2.348$, $p = 0.096$] suggesting that the Control and Dyslexia groups vary similarly across both error types and across letter grouping. In summary, children frequently report the wrong letter by confusing it with another letter in the string, especially when they are post-cued to report the middle letters. But, importantly, this error pattern does not differ across groups. Children with dyslexia are less accurate on the task overall but not due to a specific type of error.

2.6 | How does a valid exogenous spatial cue reduce errors?

In a previous study we showed that valid endogenous spatial cues reduce transposition errors for the most crowded letters in adults (Ramamurthy et al., 2021). Here we asked how valid exogenous spatial cues reduce errors in children, especially for the Dyslexia group. We calculated the difference in percent errors in the neutral cue trials compared to those in the valid cue trials separately for each letter position; this is defined as Δ errors as shown in Figure 5e,f. A LME was fit to Δ errors with error type (transposition or misidentification) and letter grouping (outer, middle, inner), groups (Dyslexia and Controls) and their interactions as fixed effects and a full random structure. We observe a significant main effect of error type [$F(1,1110) = 11.305$; $p = 0.799 \times 10^{-03}$] and letter grouping [$F(2,1110) = 20.67$; $p = 1.536 \times 10^{-09}$]. Only a two way interaction between letter grouping and error type [$F(2,1110) = 10.015$; $p = 4.889 \times 10^{-05}$] was significant. As shown in Figure 6d,

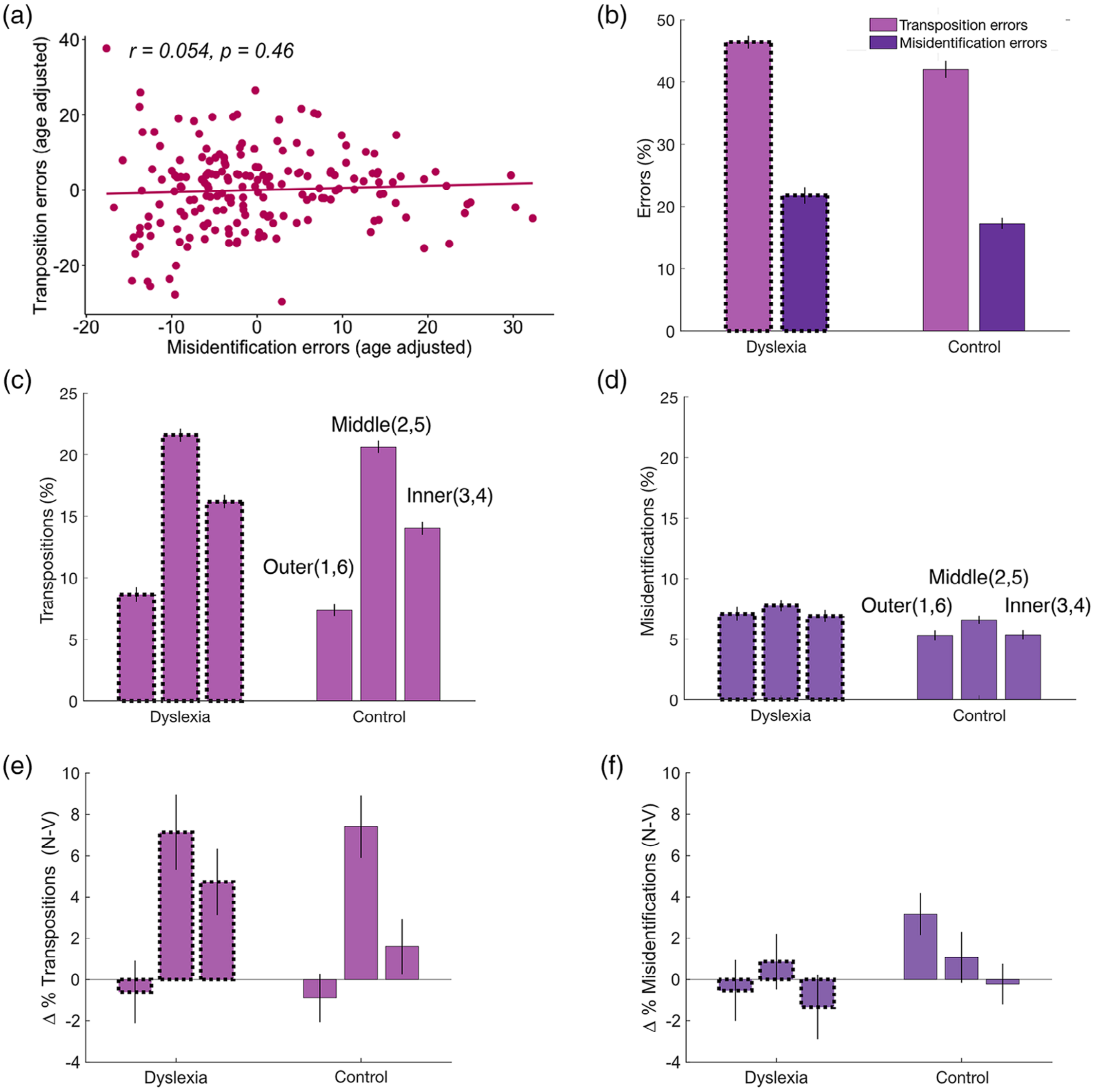

FIGURE 5 Children with dyslexia are just as likely to make letter transposition errors as typical readers. (a) Correlation between transposition and misidentification errors; (b) The percent of trials with two types of errors, namely, transposition and misidentification, for each group (Control and Dyslexia). (c) and (d) percent error type split across letter positions—calculated by number of transposition errors when the target was at this position divided by the total number of trials when the target was at this position- (outer (1,6), middle (2,5) and inner (3,4)) respectively. (e) and (f) Δ% errors were calculated by taking the difference in percent errors in the neutral cue trials compared to those in the valid cue trials. A higher (N-V) means that errors were a lot lower in the valid cue trials compared to neutral cue trials. We see that transposition errors were greatly reduced for the middle letter positions with a valid exogenous spatial cue across both groups [$t(1110) = 0.141$, $p > 0.99$, all p-values Bonferroni corrected]. Data are represented as mean ± SEM. See also Figures S3 and S4.

transposition errors are reduced more for the crowded, middle letter positions with a valid exogenous spatial cue, but this effect was not significantly different between groups [$F(1,1110) = 0.422$; $p = 0.516$].

2.7 | Exogenous spatial attention benefits left hemifield and the crowded letter position in both Control and Dyslexia groups

We know from our previous study that adults show higher cue benefits in the left hemifield (complementary to the finding that letter recognition is worse in the left hemifield) and show higher cue benefits for the middle letter positions (Ramamurthy et al., 2021). It is possible that the average effect of exogenous cues does not differ across the two groups as shown in Figure 3i–k, but children with dyslexia might show differences compared to controls in how exogenous spatial cues are utilized across different hemifield or letter groupings. To investigate how the groups differ in exogenous cue effects across the two hemifields (Figure 6a–c) we fit an LME model to attentional effects with groups and hemifields (left, right) as fixed factors. In line with previous findings, we observe that cue benefits and total cue effects are higher in the left hemifield [total cue effects: main effect of hemifield

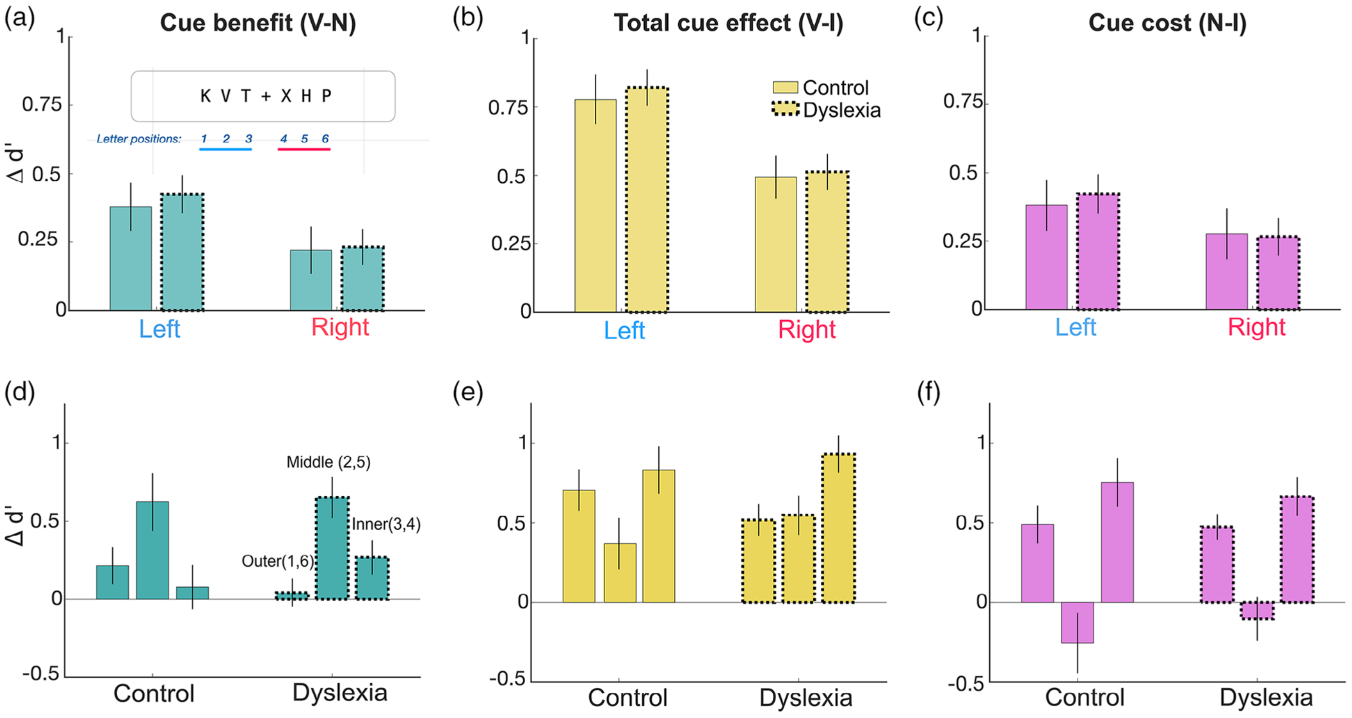

FIGURE 6 Exogenous spatial attention benefits left hemifield and the crowded letter position in both Control and Dyslexia groups. (a–c) Hemifield asymmetries in the utilization of exogenous spatial cues, and (d–f) Exogenous attention effects as a function of target letter groupings. Data are represented as mean ± SEM.

$F(1,376) = 12.683$, $p = 0.00042$; cue benefits: main effect of hemifield $F(1,376) = 7.745$; $p = 0.0057$]. We see no such hemifield bias with cue cost [main effect of hemifield: $F(1,376) = 2.790$, $p = 0.095$]. More importantly, children with dyslexia were not significantly different from the Controls in terms of hemifield asymmetries [group x hemifield interaction: total cue effects: $F(1,376) = 0.159$, $p = 0.689$; cue benefits: $F(1,376) = 2.594$, $p = 0.108$; cue cost: $F(1,376) = 0.095$, $p = 0.758$].

We then asked if children with dyslexia show position-specific differences in the utilization of exogenous spatial cues. To address this, we grouped the outer (1,6), the middle (2, 5), and the inner (3, 4) letter positions respectively. An LME model was fit to attentional effects with groups (Control vs. Dyslexia) and letter grouping (outer, inner, middle) as fixed factors. A significant effect of letter grouping means that exogenous effects are not uniform across all the positions, even though the spatial cues orient attention to three positions on the left or right of fixation. A significant interaction between groups and letter grouping means that groups differ in the way exogenous cues are utilized across different letter groupings. Cue benefits and cue cost showed significant effect of letter grouping but no significant main effect of group nor an interaction between letter grouping and groups [cue benefits: main effect of letter grouping: $F(2,564) = 19.896$, $p = 4.471 \times 10^{-09}$; groups: $F(1,564) = 0.048$, $p = 0.827$; interaction: $F(2,564) = 2.931$; $p = 0.054$; cue cost: letter grouping: $F(2,564) = 36.793$, $p = 9.569 \times 10^{-16}$; groups: $F(1,564) = 0.071$, $p = 0.789$; interaction: $F(2,564) = 0.742$, $p = 0.477$].

From Figure 6d–f, it is clear that the middle (crowded) letter positions show higher cue benefits compared to the outermost and innermost letters [difference between middle positions and the outermost positions $t(564) = 4.093$, $p = 4.889e^{-05}$ and difference between the crowded positions and the innermost positions were $t(564) = 3.384$, $p = 0.00076$]. Cue cost, on the other hand, was close to zero at the crowded letter positions, suggesting that performance between the neutral cue condition and the invalid cues were not very different at these positions which were already very low in baseline accuracy as seen in Figure 4c. These findings also show that valid exogenous spatial cues improve letter recognition at the crowded letter positions although the spatial pre-cues cued attention to all three positions on the right or left of fixation, with equal probability of the pre-cue being valid or invalid. Importantly these trends were similar for both the groups.

3 | DISCUSSION

There is long-standing controversy about the visual factors associated with dyslexia (Kristjansson & Sigurdardottir, 2023; Stein & Kapoula, 2012). Of all the measures of sensory processing that have been studied in relation to dyslexia, the multi-letter processing task has the strongest evidence for identifying a subgroup of struggling readers who are not captured by conventional measures of phonological processing (Valdois et al., 2021). Similar findings have been previously reported across French, Italian, Dutch and Chinese speakers (Huang et al., 2021; Lobier & Valdois, 2015). These results have been interpreted as a deficit in visual attention span (VAS) (Bosse et al., 2007), but this task does not involve a manipulation of attention and, therefore, does not specifically implicate visual attention (Carrasco, 2011). Thus, we sought to separate the effects of attention from visual encoding to offer a more straightforward interpretation of this phenomenon. We replicated the relationship between task performance and reading ability and, by including an attentional manipulation, demonstrated that exogenous attention is not, in fact, the limiting factor on task performance. Some previous studies that did manipulate attention with spatial cues have suggested a deficit in the exogenous spatial attention in children with dyslexia (Facoetti et al., 2000, 2003, 2006, 2008, 2010; Franceschini et al., 2012). It is not intuitive, however, why exogenous spatial attention, in particular, should be essential for reading. That is why we designed a task to isolate the effect of exogenous attention on encoding letters within a string, a task relevant for reading.

In a sample of 187 children with and without dyslexia (a sample that is roughly 3–10 times larger than most other studies on this topic), we found no relationship between exogenous attention and reading ability. We provided strong statistical support for the assertion that exogenous attention operates equivalently in children with dyslexia and control participants. We did, however, find a reliable relationship between overall letter recognition accuracy in the multi-letter processing task and reading ability. Further, we present thorough behavioral analysis that both poor and good readers exhibit reduced ability to encode letters in the left hemifield but show similar benefits when provided with a valid exogenous spatial cue. These findings go against the left hemifield neglect hypothesis in dyslexia that postulates reduced ability to recognize letters in the left hemifield specifically for poor readers (Hari et al., 2001). We showed that transposition errors are greater for the middle letter position and exogenous spatial cues reduce transposition errors, specifically, for those positions in both the control and dyslexia groups. This is surprising and deserves additional follow up since studies on visual crowding have shown that people with dyslexia suffer from excessive crowding (Bertoni et al., 2019; Geiger & Lettvin, 1987; Gori & Facoetti, 2015; Moores et al., 2011).

There is an appealing link between crowding and reading because crowding is one of the determining factors for the number of letters that can be recognized in a single fixation for typical readers (Legge et al., 2001) and is negatively correlated with reading skills in children with dyslexia (Spinelli- et al., 2002). More recently, Joo et al. (2018) showed that a subgroup of dyslexics who show excessive visual crowding benefit in reading speed when letter, word and line spacing is increased. Based on these studies we would have predicted that transposition errors for the middle (crowded) letter positions would have been greater for children with dyslexia, but we found no differences in the transposition errors compared to Controls. It is possible that our letter strings are not peripheral enough to be related to visual crowding studies; letters in our task extended an eccentricity of 1.74° on either side of fixation compared to Joo et al study where they report crowding difference at visual eccentricity of ~6°. It is nevertheless interesting that children with dyslexia show remarkable similarities in error profiles. Both transposition and misidentification errors are negatively correlated with reading ability (see Figures S3 and S4), corroborating with the main finding that task performance in the multi-letter processing task positively correlates with reading ability.

Our findings challenge previous studies that assert an exogenous attentional deficit in children with dyslexia (Facoetti et al., 2005, 2010; Franceschini et al., 2012, 2013; Fu et al., 2019). Some studies have been undergirding the sluggish shifts in attention (SAS) as a causal factor leading to reading disability. According to SAS theory, when people with dyslexia are faced with rapid sequences of stimuli, their automatic attentional system fails to disengage (or engage) efficiently, which leads to difficulty when moving from one item to the next (Facoetti et al., 2008, 2010; Fu et al., 2019; Riitta Hari & Renvall, 2001). One insight from across behavioral studies highlights the decreased pace of orienting covert spatial attention (Facoetti et al., 2005, 2010; Franceschini et al., 2012, 2013; Fu et al., 2019) often tested by varying the cue-to-target interval. In our study we manipulated the cue-to-target interval to test this, and we report no difference in performance between the 50 and 100 ms CTOA between the two groups.

Another interpretation of sluggishness could be a general slowness in processing rapid sensory information. Although our task, by design, was not a reaction time task, it is possible that exogenous spatial cues could influence the speed of letter recognition in our task differently for the Dyslexia group. When computing exogenous attentional effects using reaction time data (difference in reaction times between different cue types) we observe no correlation between reading ability and exogenous effects (see Figure S5). Thus, across both accuracy and reaction times we see no difference in the utilization of exogenous spatial cues between control and dyslexia groups lending no empirical support to the sluggish shift in attention hypothesis.

The exogenous system, by definition, responds involuntarily to salient stimuli (Chica et al., 2013). A deficit in such a system should manifest with more than one behavioral consequence affecting many behaviors other than reading. It is more likely that the endogenous voluntary attentional system is core to reading development. In fact, some researchers have alluded to this hypothesis, by questioning the specificity of the exogenous pre-cues used in some studies. For instance, Roach and Hogben, presented the strongest evidence for a deficit in covert spatial attention in adults with dyslexia, with precues that could activate both exogenous and endogenous attention. They used a simple search task, with and without informative pre-cues. Participants' task was to report the tilt direction of a single Gabor stimulus that was presented along with a variable number of vertical distractors, all equidistant from fixation. These pre-cues were both exogenous because they were peripheral and brief. And also endogenous as they provided useful information on the location of the target. In a series of additional experiments, they probed cue validity and cue-target intervals (Roach & Hogben, 2008), and concluded that the primary mechanism of the cueing effect in their paradigm was, in fact, endogenous.

White et al. (2019) used a similar paradigm adapted from Roach and Hogben and concluded that a subset of poor readers struggled to use the cue's information to focus on the target stimulus. The mechanism at play was likely endogenous spatial attention, rather than exogenous. It is for future research to investigate the role of endogenous visual attention in reading and in dyslexia. More recently, the VAS task has been interpreted as a deficit in the endogenous attentional system, albeit, without experimentally manipulating endogenous attention (Valdois, 2022). We showed, in neurotypical adults, that endogenous attention is more likely to be relevant for reading (Ramamurthy et al., 2021).

Thus, in this study we have presented the first detailed behavioral analysis of various aspects of the multi-letter processing task and the effect of exogenous spatial cues in a task relevant for reading in children with dyslexia. To understand all the visual factors that contribute to reading difficulties, it is necessary to characterize the confluence of factors associated with reading ability. Such a "deep phenotyping" approach (Delude, 2015; Robinson, 2012) could expand our understanding of the constellation of factors that cause the reading difficulty or can be a useful collection of symptoms that lends itself to identify individuals at risk early on. It is for future studies to investigate if the observed differences in multi-letter processing is a useful screening measure that can be used to categorize children at risk early in development, or a causal factor that contributes to the underlying disorder. These differences in encoding could be a very useful and timely low resource, early screening tool to categorize, follow up and intervene for children at risk.

4 | MATERIALS AND METHODS

4.1 | Participant recruitment

All participants were recruited from two research participant databases: (1) The Stanford University Reading and Dyslexia Research Program (http://dyslexia.stanford.edu) and (2) The University of Washington Reading and Dyslexia Research Program (https://ReadingandDyslexia.com). Each database includes children who have (1) enrolled and assented to being part of a research participant pool, (2) filled out extensive questionnaires on demographics, education history, attitudes towards reading and history/diagnoses of learning disabilities, (3) been validated through a phone screening to ensure accuracy of basic demographic details entered in the database. For each participant in the database a parent provided informed consent under a protocol that was approved by the Institutional Review Board at the Stanford University or the University of Washington and all methods were carried out in accordance with these guidelines. Participants in the database were first emailed a brief description of the study, with instructions to parents on the distance to sit from the screen and to let children play the game in the most attentive phase of their day. Only those participants who expressed interest in the study were recruited. After the digital consent/assent process, participants were able to access the Magic Island game and performance in the task was linked to their reading assessment data in the research database. Assessment of standardized measures of reading abilities (Woodcock-Johnson IV Tests of Achievement, Test of Word Reading Efficiency – 2), verbal abilities (Welschler Abbreviated Scales of Intelligence II (WASI-II), Vocabulary subtest) and general reasoning abilities (WASI-II, Matrix Reasoning subtest) were administered over zoom. Two hundred and eighteen children completed the reading assessments. Participants spanned the full range of reading abilities as measured by the Woodcock Johnson Basic Reading Skills (WJ-BRS) standard scores and TOWRE Index standard scores. Gender and race information were collected part of the extensive questionnaires on demographics, but since we did not have a question specific to race or gender that information was not included in the de-identified information for analysis. The age, gender and IQ scores of participants are provided in Table S1. All participants identified English as their dominant language or in par with another language based on their subject judgement on the daily usage.

Procedure and Stimulus: The experiment was built using Psychopy3 and launched online on Pavlovia (Bridges et al., 2020). The experiment was gamified to make it more engaging and fun for children. The game sets children on a mission to enter a magic island with the task to find the magic door to the island using the magic boat. The magic boat navigates using a secret map of letters. As they solve the map of letters, they move along the island one step closer to the door and are rewarded with fun creatures that join the journey. The uninformative pre-cues were introduced as random crosstalk and children were told that they are not informative. Fixation cross was introduced as the magic steering wheel on the boat and that looking away from the fixation cross would tilt the magic boat. All time epochs were designed in such a way that eye movements would not influence our results (see specifics below). Parents were instructed to seat the child at ~60 cm from the monitor. The screen background was set to full brightness and a black fixation cross ($0.5^o \times 0.5^o$) was always present at the center of the screen. The target stimuli were a string of six letters, three to the left of the fixation cross and three to the right of the fixation cross. Six consonants were randomly sampled without replacement from a set of 12 letters [B,F,H,K,L,N,P,T,V,X,Y,Z], that match on perimetric properties (Castet et al., 2017), for each trial. All letters were in monospace courier font at 100% contrast. Letter height was set to 0.5^o and the center-to-center letter spacing was 0.58^o. According to Bouma's rule (Bouma, 1973), crowding occurs if the spacing is less than half the eccentricity. Therefore, the middle letters in our experiment are likely crowded.

Trial sequence: An illustration of trial sequence with exogenous spatial pre-cues is shown in Figure 1. On each trial, after the pre-cue (described below), the participant is presented with a string of 6 letters flashed for 120 ms, three to the left and three to the right of fixation. Immediately after the letters disappear, a "post-cue" appears: a blue line under one of the letter locations. The participant's task is to report the identity of the target letter that was at the post-cue location, by clicking on one letter from a set of 12 letter choices provided. The 12 letter choices consisted of all the 6 letters (including 1 target) presented in the string along with 6 letters that were not part of that trial's string. Exogenous spatial attention was manipulated before the letters appear by "pre-cues" that direct attention to either the left or to the right three letters or to all letter positions.

Pre-cues: To elicit exogenous shifts of spatial attention to either the left or right side, the cues were red lines flashed for 50 ms under the three letter positions before the onset of the string. The exogenous cues were uninformative as to the side of the target letter to be post-cued. There was a "neutral" condition in which both sides are pre-cued, and the target could be at either side. A "valid" pre-cue is one that is on the same side as the upcoming post-cue. An "invalid" pre-cue appears on the opposite side of the post-cue. On any trial there is equal probability of a cue being valid, invalid or neutral.

Cue-target onset asynchrony (CTOA): The time interval between the onset of a pre-cue and onset of the stimulus string is the cue-target onset asynchrony abbreviated as CTOA. We used CTOAs of 50 and 100 ms. These two CTOAs were chosen based on a pilot study in which we used eye tracking to monitor stability in fixation during exogenous attentional pre-cues, and we found that the onset of a saccade (rapid eye movement) took at least 250 ms from the onset of the cue. Therefore, to avoid encoding letters in the string by making eye movements to the direction of the pre-cues, the total time from the onset of the cue to the offset of the target was kept under 250 ms.

There were five repeats for each position (6 positions), for each of the CTOAs (2 CTOAs) for each of the cue conditions (valid, invalid and neutral cue conditions) totaling to 180 trials.

Attentional effects: The effect of attention is measured as the difference in target recognition accuracy between valid, neutral and invalid trials. The cue benefit is the difference in target recognition sensitivity between valid and neutral cue trials. Cue cost is the cost of directing attention to the wrong side: the difference in sensitivity between neutral and invalid cue trials. The total cue effect, for the exogenous system, is the difference in sensitivity between valid and invalid cues. We observed no correlation between total cue effect and over task performance in the multi-letter processing task showing that the attentional manipulation was indeed orthogonal to task performance (see Figure S8).

Controls and children with dyslexia: For all analyses with groups as a factor, children were divided into Control or Dyslexia groups based on composite reading scores. Children with standardized reading scores below 1 SD (<85) on the WJ-BRS and ($n = 33$)/or ($n = 42$) TOWRE, are categorized as children with developmental dyslexia (Dyslexia group in all figures $n = 75$) and the controls are typically developing children with standardized reading ability scores above 1 SD (>85) on the WJ-BRS and TOWRE. Of the seventy-five children in the Dyslexia group, fifty had a clinical diagnosis of dyslexia (reported in the parent survey forms administered before reading assessments). Figures S6 and S7 demonstrate how effect size on task performance and attentional effects change as a function of how Dyslexia group is defined. All children had normal IQ [mean IQ: 110.05; SD: 15.46]. Figure 5a shows the age distribution of participants in the Dyslexia and Control groups respectively. The median age and standard deviations of age in both groups were comparable [Control: 9.848 ± SD: 2.173 and Dyslexia: 9.945 ± 1.845, respectively].

Data Analysis: We used the Palamedes function PAL_SDT_MAFC_PCtoDP (Prins & Kingdom, 2018), which converts proportion correct into d' for a standard M-alternative-forced-choice task, assuming an unbiased observer. For accuracy at floor (0%) we assume that had we run twice as many trials, 1 trial would be correct, so accuracy = 1/(2*Number of trials). When at ceiling (100%), we assume that had we run twice as many trials, there would be 1 incorrect trial, so accuracy = 1-(1/(2*Number of trials)).

We used linear mixed effects (LME) analyses and post-hoc t-tests to analyze accuracy across different CTOAs, groups, hemifields, letter positions, and error types. The random effects consist of subject-dependent random intercepts and slopes. We used a maximal random effects structure (random intercepts and slopes (Barr et al., 2013), in all our LME models unless specified. For example: the first LME model fit to the attentional effects (d') with fixed effects of groups (Control and Dyslexia) and hemifields (left, right) as fixed factors and a maximal random effects structure, referred to in the Results section, is written as follows in the MATLAB Statistics toolbox or with the lme4 (Bates et al., 2007) package in R: d' ∼ groups * hemifields + (groups * hemifields| subject).

Reliability: For each participant, for each cue validity condition, we computed d' separately on odd and even trials. The correlation across subjects between those split-half d' levels indicate reliability. A Spearman-Brown correction was applied to the obtained correlation to adjust for the fact that only half the trials were used. The Spearman-Brown split-half reliability for performance (d') in the multi-letter processing task, of the included 236 participants on the task, was 0.805 respectively.

Data cleaning: Task performance below 8% is chance. We calculated the 68% confidence intervals of performance for each participant and if the 68% confidence interval included chance performance, we excluded those subjects from further analysis. Of the 267 participants only 236 met this criterion. Therefore 12% of the data were lost due to unreliable performance. Further, of the 236 only 187 had reading assessments, therefore all results reported here were on those children with completed reading assessments ($n = 187$). Without excluding, we had a total of 207 children with reading assessments. We present the correlation between task performance and basic reading skills in Figures S1c and S1d, respectively.

AUTHOR CONTRIBUTIONS

Mahalakshmi Ramamurthy developed the study concept. Mahalakshmi Ramamurthy and Jason D. Yeatman contributed to the study design. Testing and data collection were performed by Mahalakshmi Ramamurthy. Mahalakshmi Ramamurthy performed the data analysis and interpretation under the supervision of Alex L. White and Jason D. Yeatman. Mahalakshmi Ramamurthy drafted the manuscript, and Alex L. White and Jason D. Yeatman provided critical revisions. All authors reviewed the manuscript and approved the final version for submission.

ACKNOWLEDGMENTS

This work was supported by research funding from Microsoft, NICHD R01-HD09586101, and the Jacobs Research Fellowship to J. D. Y. and by the Stanford Maternal and Child Health Research Institute through the Postdoctoral Fellowship awarded to M. R.

CONFLICT OF INTEREST STATEMENT

The authors declare no competing interests.

DATA AVAILABILITY STATEMENT

Data supporting this work is available at the project's Git repository https://github.com/yeatmanlab/ExoSpatialAttention_ChildrenCrossSectionalStudy

EXPERIMENT CODE AVAILABILITY

Experiment can be replicated from this repository: https://gitlab.pavlovia.org/maha10/spp_e10_kids

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

How to cite this article: Ramamurthy, M., White, A. L., & Yeatman, J. D. (2023). Children with dyslexia show no deficit in exogenous spatial attention but show differences in visual encoding. *Developmental Science*, e13458. https://doi.org/10.1111/desc.13458