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**Toward the characterization of a visual form of developmental dyslexia: Reduced visuo-attentional capacity for processing multiple stimuli made of separable features.**

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ABSTRACT

Some dyslexics cannot process multiple letters simultaneously. It has been argued that this reduced visuo-attentional (VA) letter span could result from poor reading ability and experience. Here, moving away from reading context, we showed that dyslexic group exhibited slower visual search than normal readers group for “symbols”, defined as graphic stimuli made up of separable visual features, but not for filled objects. Slowness in symbol visual search was explained by reduced VA field and atypical ocular behaviour when processing those letter-like stimuli and was associated with reduced VA letter span and impaired elementary visuo-spatial perception. Such a basic visual search deficit can hardly be attributed to poor reading ability and experience. Moreover, because it is specific to letter-like stimuli (i.e., “symbols”), it can specifically hinder reading acquisition. Symbol visual search can easily be tested in the prereading phase, opening up prospects for early risk detection and prevention of VA dyslexia.

1. Introduction

Reading is an important skill for education, work, and daily life. Developmental dyslexia (DD) is a failure to acquire efficient reading despite normal intelligence and adequate education (Rutter & Yule, 1975). The most common and sometimes the only causal deficit admitted in DD is a phonological deficit (Goswami, 2015; Hulme, 1987). However, research exploring visuo-attentional (VA) aspects has demonstrated various deficits. Several studies have reported that individuals with DD are impaired in complex serial visual search tasks (e.g., Casco & Prunetti, 1996; Iles et al., 2000; Lallier et al., 2013; Marendaz et al., 1996; Sireteanu et al., 2008). Because complex serial search requires an effortful sequential processing, this has been interpreted as caused by a general (i.e., multimodal) impairment of sequential and sustained attention in this population, that would contribute to the phonological disorder (Sireteanu et al., 2008). However slow feature-absent visual search (Casco & Prunetti, 1996; Marendaz et al., 1996) was correlated with the number of elements that can be processed simultaneously in a multiple-elements configuration (i.e., the VA span) rather than to the phonological skills of children with DD (Lallier et al., 2013). For the VA span hypothesis (Valdois et al., 2003), rather than sequential processing, the simultaneous dimension of visual perceptual attention plays a central role in reading development independently of phonology. An inability to process many characters simultaneously precludes the ability to perceive the whole word and forces the reader to use analytic grapheme to phoneme conversion. As a consequence, reading remains slow, jerky, and the irregular words cannot be well read. The established task to measure the VA span is the global report of letters (Bosse et al., 2007): a centred string of 5 consonants is displayed for 200 ms to prevent any saccadic exploration, and children have to report verbally all the letters that they can identify in any order. Note that this task measures the VA span and not a visual span because it has been shown that this span does not depend on the spacing and size of characters

(e.g., Valdois et al., 2019), it rather depends on the number of elements processed simultaneously. It therefore specifically reflects the spatial distribution of attention over visual elements. It has been shown that some dyslexics can have a reduced VA span without phonological deficit, whereas others have a phonological deficit with preserved VA span (Bosse et al., 2007). The tenets of the VA span theory claim that DD could be caused by either a VA span deficit or a phonological deficit, or both (Bosse et al., 2007; Zoubrinetzky et al., 2016). Still, the VA span theory has been and remains very controversial. First, the role of the VA span in DD has been minimized because it is rarely observed in isolation from phonological deficits (Saksida et al., 2016). Second, some authors claim that a VA deficit is a consequence of a specific linguistic deficit and poor reading experience instead of a cause of DD (Goswami, 2015). One could conceive that the global report of letters could be impaired due to a deficit or slowness in naming consonants or due to less experience in mental scanning of horizontal strings that would be obtained through reading practice. However, if the VA span deficit was a consequence of DD, one could then wonder why it would not be observed in a majority of cases. Furthermore, Lobier and Valdois (2015) mention that reduced VA span dyslexics also demonstrate incomplete report for non verbal symbols in tasks that require categorization responses instead of verbal report (Lobier, Peyrin et al., 2012; Lobier, Zoubrinetzky, et al. 2012). Following Vellutino (1979), Goswami (2015) in turn argued that, even with unfamiliar visual stimuli, recognition and retention may be mediated by verbal labelling. To address these concerns as well as those regarding horizontal scanning, the laboratory visual search task would seem to be an excellent paradigm since it uses non-verbal and even non-representational stimuli that are randomly organized in space. It does not involve any visual-to-phonological mapping nor any verbal labelling because it does not involve real object recognition, categorization or retention for recall. It rather and solely involves visual feature integration and discrimination of a unique target across many trials (Treisman & Gelade, 1980). The third argument raised against the VA span theory is that it should explain how a visual deficit will specifically impair only reading ability and not lead to a more general impairment of visually based functional abilities (Goswami, 2015). In accordance with this requirement of specificity, it has been reported that the VA span is not reduced for the report of colour disks (Valdois et al., 2012). Thus, the crucial problem appears to be the specific visual properties of “symbols”. Note for clarity that we do not use the term “symbols” here in its colloquial definition (e.g., “a thing that represents or stands for something else ...”, Oxford Languages). Instead, we define “symbols” here as stimuli with a particular set of visual properties – a spatial combination of curved and straight lines sometimes completed with dots – that have been typically designed by humans for written languages because they are signs that could be easily made with wedges on tablets or ink on paper (Daniels, 1996). Such complex marking systems have gradually replaced the early filled and coloured pictorial signs that could be processed as real objects. Instead, these non-natural unfilled “symbols” made of spatial combinations of strokes have become very specific cultural images whose visual processing requires a specialized non-innate neural circuit, and explicit effortful learning (Dehaene & Cohen, 2007). The basic impairment in the VAprocessing of the typical spatial combinations of strokes of written language symbols could hinder reading acquisition, independently of any impairment concerning their representational meaning. Note that complex serial search tasks, repeatedly reported impaired in DD, usually involve symbols, as defined above as graphic stimuli made up of strokes similar to letters. Specific difficulties in processing symbols have been demonstrated in two visual search studies. First, comparing visual search performance between poor and good readers, Casco and Prunetti (1996) showed that poor readers were slow only in specific visual search conditions involving shapes made up of the spatial combination of separable features: a single tilted bar was found as quickly as controls among single vertical bars but search was impaired in poor readers when this tilted bar was combined with others to form a symbol (e.g., complex target stimulus K (or non-alphabetic symbol) among a set of identical distractors F (or non-alphabetic

symbols)). Second, Khan et al. (2016) made a similar observation in a patient with a bilateral superior parietal lobule (SPL) lesion recovering from clinical simultanagnosia – a deficit of simultaneous visual processing (Wolpert, 1924). The patient was significantly slower than controls for pop-out or serial search displays involving symbols made up of a combination of strokes (e.g., in a feature-absent task consisting of finding a circle among lollipops made up of a combination of a vertical bar crossing a circle – note that the patient reported perceiving either the circle or the bar of the lollipop but rarely both at the same time-, or when processing complex Chinese-like characters with a line present or with a line absent) but not for pop-out or serial search displays involving filled objects (e.g., finding a black disk among filled lollipops – in this case perceived as single units – or a red disk among red squares, or among red squares and green disks). A moving window paradigm (McConkie & Rayner, 1975) demonstrated that this slowness, specifically observed when the search task involved stimuli made up of separable features, was associated with a reduced VA field that can be mimicked in control subjects by artificially applying a reduced gaze-contingent search window. Moreover, when the patient performed the visual search with an artificially reduced gaze-contingent search window, this did not impair her performance, confirming that it was fitting her natural visual attentional window when processing symbols (Khan et al., 2016). Thus, the perceptual spatial binding of unfamiliar symbols similar to letters was problematic and associated with a reduced VA window in this SPL-damaged patient while filled unfamiliar shapes were processed normally. This result is of particular interest if we aim to demonstrate a VA deficit that would specifically hinder reading acquisition, and if one considers that the SPL has been identified as the key region underlying the VA deficit in DD (Lobier et al., 2014; Peyrin et al., 2012). Different brain regions have been identified by neuroimaging studies for the 2 deficits, phonological and VA, identified as potentially causing DD. The phonological one is the most often described, involving the superior temporal area, the supramarginal gyrus and the frontal inferior gyrus of the left hemisphere (Jobard et al., 2003). For the VA deficit, it has been shown that the SPL is activated bilaterally when several elements have to be processed at the same time but not during the processing of a single element (Lobier, Peyrin et al., 2012). Another neuroimaging study showed that the SPL was not activated bilaterally in dyslexics when they had to process several elements simultaneously (Lobier et al., 2014). Finally, a neuroimaging study compared 2 dyslexics, one with a phonological deficit but a normal VA span and one with a reduced VA span but normal phonological skills. The one with the phonological deficit exhibited normal activation of SPL in the multiple elements task but decreased activation of the left hemisphere language areas in a phonological task. In contrast, the dyslexic with a reduced VA span exhibited normal left hemispheric inferior fronto-temporo-parietal activation during the phonological task but abnormal SPL activation during the multiple elements task (Peyrin et al., 2012). A recent white matter Diffusion Tensor Imaging analysis confirmed this double dissociation in brain-behaviour relations in 26 DD children (Liu et al., 2022). Our hypothesis is that common attentional resources of simultaneous visual processing are shared for the spatial binding of letter-like symbols made up of separable visual features and for extending the attentional spotlight. Whether attention is distributed over a spatial window – VA field – or over a specific number of objects – VA span – depends on the possibility of visually grouping the non-target objects when they are identical, as demonstrated by Vialatte, Saleme, et al. (2021). Bilateral SPL lesions produce a primary deficit of relative localization of multiple elements both within and between objects (Vialatte, Yeshurun, et al., 2021) affecting some aspects of perceptual organization. Objects automatically capture attention (Yeshurun et al., 2009). Symbols, unlike filled objects, contain multiple concavities analysed as elements of a single perceptual unit that need then to be grouped by the visual attentional system (Palmer & Rock, 1994). We speculate that, not being processed and identified globally, symbols would be considered as multiple objects, each stroke would attract its own focus of attention, thereby reducing the resources of distributed spatial attention required for simultaneous visual

processing over the visual display. Unless the deficit is as severe as in simultanagnosia patients in the acute stage following bilateral SPL lesion (Michel & Henaff, 2004), reduced VA resources for simultaneous visual processing in DD would not preclude the processing of multiple filled objects or of single symbols. However, it would hinder the simultaneous processing of multiple symbols, a specific situation that combines the demands of both spatial integration within element and between-element. Such condition is seldom in everyday life but is systematically encountered during reading acquisition, until visual recognition of letters and words as single-units is acquired. In the present study, we aimed at testing this hypothesis by investigating whether dyslexics who are specifically slow in the visual discrimination of symbols also display a reduced VA field for symbols but not for filled objects. We, therefore, contrasted in children with DD the same two conditions of visual search consisting of finding a unique circle (versus disk) among identical distractors (empty versus filled lollipops, respectively, see Figure 1) and used the same moving window paradigm as in Khan et al. (2016). If a VA field shrinkage is observed only when faced with the requirement of spatial integration of separable features (e.g., for letter-like symbols) but not when stimuli are filled objects, then this would explain why a VA deficit would specifically affect reading material and causally contribute to the DD of these children. As a secondary aim, to examine whether they are associated with slow symbol search and therefore reflect a common underlying deficit of simultaneous processing, we investigated other visual tasks for which reduced performance has been reported in the literature of both DD and simultanagnosia such as (i) the global report of consonant strings (VA span, Figure 3; Bosse et al., 2007; Valdois et al., 2019), (ii) the elementary visuo-spatial perceptual comparison of simple spatial configurations and shapes (EVSP test, Figure 4; Pisella et al., 2013, 2021), as well as (iii) the automatic perception of global shapes made up of multiple local ones (Figure 2; Franceschini et al., 2017; Bedoin, 2017; Clavagnier et al., 2006). We predicted the following: (i) since the reduced VA field and span are two sides of the same coin in SPL-damaged patient IG – a deficit specific for symbols (Khan et al., 2016; Vialatte, Salemmé, et al., 2021; Vialatte, Yeshurun, et al., 2021), we expect that dyslexic children showing slow symbol search will also be impaired in VA span, (ii) impairment at the EVSP test (Figure 4) will also be associated with slow symbol search since it requires processing the spatial configuration of multifeatured stimuli that can be considered as symbols. For the local/global shape report task, we chose the stimuli involving small filled objects used by Franceschini et al. (2017) (Figure 2) to potentially allow us to isolate a general global attention deficit from the symbol-specific reduced VA ability. Such a general attention deficit will not be systematically associated with symbol-specific slow visual search in dyslexic children.

## 2. Methods

### 2.1. Subjects

74 Children aged between 8 and 12 with or without DD were recruited. They had to display normal or corrected-to-normal vision and no history of neurological deficit. All volunteers' parents gave written informed consent to this research. Experimental procedures were approved by the French health research ethics committee (CPP Ile de France VI, 2017-A02525-48). Among this pool, 52 children were dyslexics, diagnosed according to the Diagnostic and Statistical Manual of Mental Disorders (Crocq et al., 2016) criteria and based on the various clinical tests administered by their speech therapists (available in Appendix, Table A2, for 46 children whose families gave us access to these data). They did not have any diagnosed comorbidities like developmental coordination disorder, oral language disorder or attentional disorder with or without hyperactivity. Based on their visual search performance, the dyslexic children were further divided into two groups: DysFast and DysSlow (see section 2.3.1). The remaining 22 children displayed typical development and schooling achievement

with no history of learning deficit, they constituted the Normal Reader group and performed the exact same tasks as the dyslexic children described below.

## 2.2. Tasks

### 2.2.1. "Alouette" reading test

"L'alouette" is a French reading test that consists of a text without meaning (Lefavrais, 1967). The experimenter records the number of errors and the time to read the text within 3 min. A table provides a reading age that can be compared with the chronological age of the subject. This sensitive reading test, which is used more in research than in clinical contexts, was administered to check that the dyslexic children performed at a level below the pathological threshold of 18 months delay and that the control children did not.

### 2.2.2. Visual search tasks

Children sat in a semi dark room with their eyes at a distance of 57 cm from a computer screen (40 × 30 cm, refresh rate: 60 Hz, resolution: 1280\*1024), and their forehead and chin stabilized. Their eye positions were monitored by an eye tracker (EyeLink® portable duo) at 1000 Hz and the trials were developed, displayed and recorded with Experiment Builder® software (SR research, Canada). Each trial began with a central fixation cross. Children had to fixate it for 1s to bring up the visual search display on the screen which remained until a button press. Children had to look for the target among distractors. There were 2 kinds of visual displays in blocked conditions: those made with filled objects and those with symbols composed of separable features. In the filled object condition, they had to find the black disk among black-filled lollipops (black disks with vertical bars, Figure 1 – left panel). In the symbols condition, they had to find the circle among empty lollipops (circles with vertical bars, Figure 1 – right panel). The target measured 1.3° of visual angle and could appear in one of the four quadrants of the visual search display (upper-left, upper-right, lower-left, lower-right), at a random location on a virtual perimeter of 7.5° or 12.5° around the initial fixation position, and among 24 or 48 distractors (the items were distributed homogeneously across space pseudo-randomly, with a minimum spacing between them of 1.3°). Each block consisted of 32 target-present displays (2 repetitions of each target eccentricity, quadrant and set-size) and 4 target-absent displays (2 for each set-size) resulting in a total of 36 trials (randomly presented). Additionally, children performed the visual searches in two blocked experimental sessions: full view (no gaze-contingent visibility window) and reduced view (gaze-contingent visibility window). In the gaze-contingent visibility condition, a circular window of 20° diameter moved along with the gaze thanks to the high-frequency eye tracker and masked peripheral vision. Altogether, each child performed 4 blocks of 36 visual searches (144 trials) in the following order: Filled objects / full view - Filled objects / reduced view - Symbols/ full view - Symbols/ reduced view The instruction was to respond as quickly as possible by pressing the right arrow key of the keyboard when the target was present in the visual display and the space bar if they were sure that the target was absent. We recorded the reaction time (RT) of a button press after the visual display presentation. Erroneous trials were removed from the visual search time analysis. They consisted of false alarms (when they said the target was present when it was not), which did not exceed 2.2%, and false negative errors (when children said the target was absent when it was present), which reached 5.8% in the dysSlow group. With these latter trials, if the children had searched longer, they would likely have found the target, and if these trials had been kept, they would have increased the mean RT. Since false negative errors artificially decreased the mean RT, we computed a corrected RT score for each condition and each subject:  $\text{meanRT} + (\text{meanRT}(1 - \text{efficiency}))$  where efficiency was the proportion of correct answers. We also recorded exploratory eye movements during the four blocks of visual search. Saccade and fixation were categorized off

line as in Vialatte, Saleme, et al. (2021). The scanning saccade detection threshold was set at 500°/s and fixation was considered to have occurred if the gaze remained within a spatial dispersion threshold of 1.5° on both vertical and horizontal coordinates for at least 50 ms. Saccades that began between 0 and 100 ms after the appearance of the stimulus array were considered anticipatory and were not included in the analysis. To account for the decision time, we also did not consider saccades that took place within 70 ms from the button press time. We removed one child from the DysFast group and one from the DysSlow group from this analysis because their eye movement recordings were not usable due to noise.

### 2.2.3. Local/global attention task (Figure 2)

Participants sat in a semi-dark room with their eyes at a distance of 50 cm from the screen (40 × 30 cm, refresh rate: 60 Hz, resolution: 1280\*1024). The stimuli were redrawn from Franceschini et al. (2017). Different geometric shapes were displayed on the screen: a square (11.5\*11.5° of visual angle) made of small filled squares (Figure 2(1A)) or small filled triangles (Figure 2(2A)) (1.4\*1.4° of visual angle); or a triangle (11.5\*11.5° of visual angle) made of small filled triangles (Figure 2(1B)) or small filled squares (Figure 2(2B)) (1.4\*1.4° of visual angle). There were thus 2 types of congruent stimuli (where the global and the local shapes were the same) and 2 types of incongruent stimuli (where the global and local shapes were different). Two sessions were run, the global identification session where the child had to report the global geometric shape (triangle or square), followed by the local identification session where the child had to report the small shapes (triangles or squares) that made the global shape. There were 56 trials per session (global and local), composed of 28 congruent and 28 incongruent trials. Each trial began with a central fixation cross of 1s duration replaced by the stimulus displayed at the centre of the screen. The child had to respond as quickly and accurately as possible by pressing the right arrow key (with the right index finger) for the square and the left arrow key (with the left index finger) for the triangle. The stimuli remained on the screen until the response was given. Response time and accuracy were recorded for the four different task (local/global) and congruency conditions. We computed a corrected RT score for each condition and each subject:  $\text{meanRT} + (\text{meanRT}(1-\text{efficiency}))$  where efficiency was the proportion of correct answers. Then we computed an interference score separately for the local and global tasks sessions as the corrected RT score of incongruent condition trials minus the corrected RT score of congruent condition trials. Interference scores are expected to be positive values since RT in incongruent trials is supposed to be longer than in congruent trials, especially in the local task. In incongruent trials, dyslexic children have been shown to exhibit reduced interference from the global shape in the local task, and increased interference from the local shapes in the global task, suggesting that their attention is abnormally focused on local shapes (Franceschini et al., 2017). We calculated the interference asymmetry index as the interference score in the local task minus in the global task. Usually, the global precedence effect is observed, meaning that the small shape will less interfere with the processing of the global shape than the reverse, so the interference score is larger in the local task and the interference asymmetry index is positive. In dyslexic children, low index has been reported, showing that they do not display the normal global precedence effect (Bedoin, 2017).

### 2.2.4. Global report task (Figure 3)

We used the global report task of the EVADYS software (<https://www.happyneuronpro.com/orthophonie/espace-evaluation/evadys/>) to assess the VA letter span (Bosse et al., 2007). Participants sat in front of a screen at 50 cm, fixated a central cross during 1s, then a blank screen was presented for 50 ms, followed by a centred string of 5 consonants displayed for 200 ms to prevent any saccadic exploration. They had to report verbally all the letters that they could identify in any order. There was a familiarization task of 10 trials followed by the presentation of 20 strings of 5

consonants. We recorded the accuracy, each correct letter report was assigned 1 point, resulting in an individual score out of 100 for each subject that could be compared to age-based norms provided by the software.

### 2.2.5. Elementary visuo-spatial perception (EVSP) test (Figure 4)

Each participant sat at a table and the visual stimuli were presented one at a time on A4 white sheets of paper. The child was requested to compare spatial relationships of stimuli that were composed of disks (T2), combinations of multiple lines (T1, T3, T4), or combinations of lines and dots (T5, T6). In this respect, this test requires visual comparisons of “symbols”. As can be seen in Figure 4, subtests of T1, T2, T3, and T5 relied on image-pair comparisons that require a “same” or “different” response, respectively targeting Length, Size, Angle, and relative Position. Subtest T4 required a midline judgement and subtest T6 required a dot position selection. In each subtest there are 12 trials with 1 point assigned to each correct answer. Therefore, the total score was a maximum of 72 points which could be compared to age-based norms (available in Pisella et al., 2020). 50% of the children with a specific learning deficit have been shown to score below the interquartile range of this test (Pisella et al., 2021).

### 2.3. Data analysis

The data were analysed in several steps. The first step consisted of comparing reaction time performance in visual search between DDs and Normal Reader groups and evaluating if it was possible to define two groups of DDs: Fast and Slow. The second step consisted of comparing the performance of the three experimental groups DysFast, DysSlow and Normal Reader on reaction times but also on the other variables of the visual search task and to cross-reference these results with the variables Visibility (Reduced or Full View) and Condition (Filled Objects or Symbols). Finally, the performance of the three experimental groups was compared on the other tasks. All these steps are described below.

#### 2.3.1. Visual search analysis

##### 2.3.1.1. Search time.

In order to test whether we confirm the data reported by Casco and Prunetti (1996) in our sample, we first carried out repeated measures ANOVA on the mean RT scores with Condition (Filled Objects or Symbols) as the within subject factor and Group as the between-subject factor, considering only Full View data and contrasting only two groups (DD versus NormalReader). Post-hoc comparisons consisted of 2 unpaired ttests contrasting the performance of the two groups, separately for Filled Objects and Symbols search conditions. Based on their individual visual search performance (Appendix, Table A4) in Full View, the dyslexic children were further divided into two groups. We computed the individual difference between the means RT scores observed for Symbols and Filled Objects search conditions. We compared the individual performance of each dyslexic child with the mean and standard error of the NormalReader group using a one-tailed Crawford modified t-test (Crawford & Howell, 1998). Each dyslexic child whose RT difference was significantly larger than the NormalReader group was placed in the DysSlow group (they were specifically slow for Symbols visual search). The others formed the DysFast group. In the second step, comparisons involving the independent variables Visibility (Reduced or Full View), Condition (Filled Objects or Symbols) and Groups (DysFast, DysSlow and NormalReader) were carried out using linear mixed effects modelling in order to separate the expected fixed effects of these variables from the random effects due to the variability of the subjects' responses. The model equation was defined to take also into account the interaction effects between these three independent variables. In this case, the number of fitted



parameters of the linear model is very large and we have therefore chosen to present the significance of the results in the form of Fisher tests comparing the variances from the model with the residual variances. In this way, the main effects of each of the independent variables as well as their interaction effects could be determined. These calculations were carried out using R software and the following formula:  $\text{lmer}(\text{search time} \sim 1 + \text{condition} + \text{group} + \text{visibility} + \text{condition}:\text{visibility}:\text{group} + (1|\text{subject}), \text{data}, \text{REML} = \text{TRUE})$ . Then we carried out post-hoc comparisons consisting of 6 FDR-corrected paired t-tests contrasting performance in Reduced and Full view within each Group, separately for Filled Objects and Symbols search conditions.

#### 2.3.1.2. Search accuracy.

The percentage of false negative and false alarms of the visual search tasks was compared between the three Groups (DysFast, DysSlow, and NormalReader) of participants using a Chi-Square analysis.

#### 2.3.1.3. Ocular behaviour analysis.

For the exploratory eye movement analyses, we carried out the same procedure as above, i.e., applying a mixed linear model on the mean number of saccades, the mean fixation time and the mean saccade amplitude with the same three variables (Condition, Visibility and experimental Groups). To resolve the significant interaction effects, post-hoc comparisons were performed using FDR-corrected paired and unpaired t tests.

#### 2.3.2. Other parameters and tasks analysis

Comparisons between the three Groups (DysFast, DysSlow, and Normalreader) were carried out with unpaired t-tests for chronological and reading age, mean RT difference (symbols-filled objects) in visual search, VA span score in the global report test, score in the EVSP screening test and interference asymmetry index at the Local/Global discrimination task. Modified t-tests were also implemented for the Local/Global discrimination task for which we did not have normative values, in order to compare the performance of each individual with DD to the control NormalReader group (Crawford & Howell, 1998).

### 3. Results

#### 3.1. Visual search and DD

We first compared the mean RT scores between the whole sample of dyslexic children (52 children with a diagnosis of DD; mean chronological age =  $121.38 \pm 12.11$  months, mean reading age =  $89.10 \pm 7.87$  months) and the sample of normal readers (22 children with no diagnosis of DD; mean chronological age =  $122.77 \pm 15.25$  months, mean reading age =  $114.32 \pm 19.23$  months). This way, we confirmed the results of Casco and Prunetti (1996) for this group of children diagnosed with DD (Figure 1). Repeated measures ANOVA showed a significant interaction effect between diagnosis group (DD versus Normal readers) and type of stimuli (Filled Objects versus Symbols) ( $F(1,72) = 4.86$ ,  $p < 0.05$ ). Visual search for Symbols was significantly slower in dyslexics (DD: mean = 3636 ms SD = 1358; Normal readers: mean = 2965 ms SD = 1358;  $t = -2.69$ ,  $p < 0.05$ ), but not visual search for Filled Objects (DD: mean = 3113 ms SD = 1007; Normal readers: mean = 2900 ms SD = 661;  $t = -1.08$ ,  $p = 0.29$ ). As expected, not all dyslexic children individually increased their RT score between Filled Objects and Symbols conditions. Therefore, as detailed below, the RT scores were further analysed to constitute two behavioural groups of dyslexics.

#### 3.2. Behavioural groups

The dyslexic children were divided into two groups according to their visual search performance in Full View. We computed the individual difference between the means RT scores observed for Symbols and Filled Objects search conditions. We compared the individual performance of each dyslexic child with the mean and standard error of the NormalReader group using a one-tailed Crawford modified t-test (Crawford & Howell, 1998). Each dyslexic child whose RT difference was significantly larger than the NormalReader group was placed in the DysSlow group (they were specifically slow for symbols visual search). The others formed the DysFast group. The final groups were composed of 20 children for the DysSlow group (mean chronological age = 120.00 ± 10.26 months, mean reading age = 89.20 ± 6.64 months) and 32 children for the DysFast group (mean chronological age = 122.25 ± 13.22 months, mean reading age = 89.03 ± 7.12 months). The 3 groups had the same chronological age ( $t_s < 0.7$ ,  $p_s > 0.05$ ), and the NormalReader group had a greater reading age than both the DysFast group ( $t = 5.90$ ,  $p < 0.05$ ) and the DysSlow group ( $t = 5.76$ ,  $p < 0.05$ ). The two dyslexic groups had similar reading age ( $t = -0.087$ ,  $p = 0.93$ ). The percentage of false negative errors did not differ between groups (NormalReader: 3.9%, DysFast: 3.5%, and DysSlow: 5.8%;  $X^2 = 6$ ,  $p = 0.2$ ) as well as the percentage of false alarms (NormalReader: 2%, DysFast: 0.78%, and DysSlow: 2.2%;  $X^2 = 4$ ,  $p = 0.2$ ). As expected, the mean RT difference (symbols – filled objects) of the DysSlow was significantly different from the NormalReader group ( $t = -7.47$ ,  $p < 0.05$ ) and from the DysFast group ( $t = 7.78$ ,  $p < 0.05$ ). These two last groups were not significantly different from each other ( $t = 0.81$ ,  $p = 0.42$ ).

### 3.3. Effect of gaze-contingent visibility window on search time

Results from the linear mixed model showed significant main effects of Group ( $F(2,71) = 3.2$ ,  $p < 0.05$ ) and Condition (Filled Object vs Symbol) ( $F(1,71) = 5.5$ ,  $p < 0.05$ ). There was also a significant interaction group: condition: visibility ( $F(2,71) = 12.8$ ,  $p < 0.05$ ). We performed FDR-corrected paired t-tests for intergroup comparisons between the 2 visibility sessions for each stimulus type. In the Filled Objects condition, all three groups showed a significant increase of their mean RT in the Reduced compared to the Full View (NormalReader:  $t = -5.5$ ,  $p < 0.05$ ; DysFast:  $t = -6.2$ ,  $p < 0.05$ ; DysSlow:  $t = -6.3$ ,  $p < 0.05$ ). In the symbols condition, only the NormalReader ( $t = -3.5$ ,  $p < 0.05$ ) and the DysFast ( $t = -4.1$ ,  $p < 0.05$ ) groups increased significantly their mean RT with Reduced View. The DysSlow group performed similarly in Full and Reduced View ( $t = -0.61$ ,  $p = 0.55$ ), i.e., their search performance was not affected by the reduced moving window, demonstrating that they already used a reduced VA field of search in full view specifically when they had to process symbols (Figure 5).

### 3.4. Exploratory eye movement patterns

Exploratory eye movement pattern of children with DD inside or even outside the reading context have been characterized as atypical and sometimes considered as potential oculomotor causes of poor reading performance, together with aberrant cognitive-linguistic processes (Franzen et al., 2021; Pavlidis, 1981). We hypothesized that atypical ocular parameters would not be present by default in most cases of DD but rather result from the reduced attentional window of dyslexic children with a VA profile when faced with letters. In the visual search task (which doesn't involve linguistic processing), a different exploratory eye movement pattern was therefore expected only in the DysSlow group and only in the condition involving Symbols. This was tested by contrasting ocular parameters in Full View between groups. Another way to evaluate the possibility of a significant three-way interaction was to compare the ocular parameters of each group between Full and Reduced View. If the artificially reduced view does not alter the ocular profile of the DysSlow group, it means that their useful field of view is even smaller than the artificial visibility window. If the artificially reduced view alters the ocular parameters of the NormalReader group and makes them approach qualitatively the atypical ocular profile of the DysSlow group, then it means that this ocular profile depends on the size of the useful field of view, further suggesting that atypical ocular pattern

is not a cause or a consequence of dyslexia but rather a consequence of reduced window of visual processing (Prado et al., 2007).

#### 3.4.1. Number of saccades (Figure 6(A))

Results from the mixed linear model on the mean number of saccades showed a significant three way interaction group: condition: visibility ( $F(2,69) = 6.4, p < 0.01$ ). We performed FDR-corrected unpaired t-tests between groups for each stimuli type explored in full view. For the filled objects condition, the 3 groups were not different ( $-1.2 < t < 0.9, p > 0.46$ ). For the symbols condition, children in the DysSlow group made significantly more saccades than NormalReader ( $t = -3.6, p < 0.05$ ) and DysFast ( $t = -3.7, p < 0.05$ ) groups. NormalReader and DysFast groups were not different ( $t = -0.01, p = 0.99$ ). To further examine the significant three-way interaction, we also carried out specific post-hoc comparisons between the number of saccades performed by each group when they explored the two stimulus types with an artificially Reduced View and without (Full View). All groups increased their number of saccades with reduced visibility when processing Filled Objects ( $-5.8 < t < -4.2$ ; all  $p < 0.01$ ), suggesting that their useful field of view was larger than the visibility window of  $20^\circ$  in this condition. This was also the case when processing Symbols ( $-4.1 < t < -2.6$ ; all  $p < 0.01$ ), except for the DysSlow group ( $t = 0.1; p = 0.91$ ), which suggests that this latter group displayed a useful field of view smaller than  $20^\circ$  in this stimulus condition.

#### 3.4.2. Fixation time (Figure 6(B))

There was a significant three-way interaction group: condition: visibility ( $F(2,69) = 27.1, p < 0.01$ ) on the mean fixation time. We performed FDR-corrected t tests between Groups for each stimuli type explored in Full View. For the Filled Objects condition, the 3 groups were not different ( $-1 < t < 1.2, p > 0.45$ ). For the Symbols condition, children in the DysSlow group displayed significantly longer fixations than NormalReader ( $t = -3.8, p < 0.05$ ) and DysFast ( $t = -3.8, p < 0.05$ ) groups. NormalReader and DysFast groups were not different ( $t = -0.29, p = 0.93$ ). To further explore the significant three-way interaction, we also carried out specific post-hoc comparisons between the mean fixation time of each group when they explored the two stimulus types with an artificially Reduced View and without (Full View). All groups increased their mean fixation time with reduced visibility when processing Filled Objects ( $-12.1 < t < -9$ ; all  $p < 0.01$ ), suggesting that their useful field of view was larger than the visibility window of  $20^\circ$  in this condition. This was also the case when processing Symbols ( $-5.8 < t < -5.2$ ; all  $p < 0.05$ ), except for the DysSlow group ( $t = 2.1; p = 0.91$ ), which suggests that this latter group displayed a useful field of view smaller than  $20^\circ$  in this stimulus condition.

#### 3.4.3. Saccade amplitude (Figure 6(C))

Regarding saccade amplitudes, these were smaller for Symbols (main effect  $F(1,69) = 10.5, p < 0.01$ ) and Reduced visibility (main effect  $F(1,69) = 247, p < 0.01$ ), and the significant interaction ( $F(1,69) = 12.8, p < 0.01$ ) showed that Reduced visibility decreased more the saccades amplitudes for Filled Objects. There was no main effect of Group ( $F(2,69) = 0.16, p = 0.85$ ) but a significant three-way interaction of group: condition: visibility ( $F(2,69) = 19.5, p < 0.05$ ). All two-by-two post-hoc comparisons between Groups revealed no statistical differences (all  $ts < 2.21$ ), and all two-by-two post-hoc comparisons between Reduced and Full View were significant (all  $ts > 7.65$ ), but FDR-corrected t-tests showed smaller saccade amplitude for Symbols relative to Filled Objects in Full View for the NormalReader ( $t = 3.13; p < 0.01$ ) and DysFast ( $t = 2.56; p < 0.01$ ) groups and not for the DysSlow ( $t = 1.28; p = 0.30$ ) group. This confirms that the DysSlow group displayed an atypical ocular behaviour when processing Symbols.

### 3.5. Performance of the three groups on the additional visual tasks (local/global attention, global report of letters strings, EVSP)

For the local / global attention task

(see Figure 2), the interference asymmetry index (described in methods: the lower this index, the more the child is affected by local interference) did not differ significantly between groups ( $t_s < 1.8$ ,  $p_s > 0.05$  for all student t test comparisons between groups). This was mainly due to the large variability observed in the two dyslexic groups. Because there are no published norms with this version of the task, we tested for each dyslexic child, individually, whether the index was significantly smaller than the mean and SD observed in our NormalReader group using one-tailed Crawford modified t-test (Crawford & Howell, 1998). We distinguished 2 age categories ( $= 10$  years) because the global preference appears around 9 years (Poirel et al., 2008). Mean and SD for the NormalReader group were  $12.54 \pm 101$  for children younger than 10 years old, and  $44.35 \pm 98$  for children aged 10 years or more. We found 5 children in the DysFast group (16%) who displayed an asymmetry index significantly smaller than the NormalReader group, and none in the DysSlow group (Appendix, Table A1). For the VA letter span assessed with the global report task (20 5-letter strings flashed during 200 ms, see Figure 3), the NormalReader group scored above both the DysFast ( $t = 5.0$ ,  $p < 0.05$ ) and the DysSlow ( $t = 3.57$ ,  $p < 0.05$ ) groups (for raw data see Appendix, Table A2). DysFast and DysSlow groups also had a similar percentage of children who performed below normative interquartile ranges (available separately by grades in Bosse et al., 2007): 75% of the DysFast group, 70% of the DysSlow group, and 14% of our own NormalReader group. For the Elementary visuo-spatial perception (EVSP) test (including 6 subtests testing respectively length, size, orientation, midline, dot-square position comparison and selection, see Figure 4), only the DysSlow group scored significantly below the NormalReader group ( $t = 2.34$ ,  $p < 0.05$ ). Based on normative interquartile ranges that are available separately by age categories, as detailed in Pisella et al. (2021), we further classified each individual global score. About 12.5% of the children in the DysFast group scored below the interquartile range of their age category, 30% did so for the DysSlow group and none for our NormalReader group. We also looked at the subtests that were the most difficult for DD (See raw data on Appendix, Table A3): no subtest specifically popped out in the DysFast group, but half of the individuals in the DysSlow group scored below the interquartile range for horizontal Midline judgement and Position selection (50% and 55% for T4 and T6 respectively). Table 1 provides the mean and standard error for each group and each test, and summarizes the behavioural profile of the dyslexics of the DysSlow and the Dysfast groups in the present study, as also summarized below.

DysSlow (20 children): • More temporal cost than normals in visual search when stimuli are symbols compared to when they are filled objects • Abnormal eye movements in visual search when stimuli are symbols (more numerous saccades and longer fixation time than normals, saccade amplitude not significantly reduced compared to filled objects condition) • Not affected in visual search for symbols by reducing visibility with a gaze-contingent search window • Lower letter span at the global report task than normal • Worse than normal at the elementary visuospatial perception test • None showed an abnormal local/global asymmetry effect

DysFast (32 children): • No pathological cost in visual search when stimuli are symbols • Normal eye movements in visual search whether it involves symbol or filled objects • Affected in visual search by reducing visibility with a gaze-contingent window whether it involves symbol or filled objects • Lower letter span at the global report task than normals • Within normal range results on the elementary visuospatial perception test • 5 of them showed an abnormal local/global asymmetry effect (not significant at group level)

#### 4. Discussion

It is recommended to study non-linguistic deficits outside the reading context in order to successfully demonstrate their causal role in developmental dyslexia ("Any visual attention task

based on letters or requiring oral reporting is inherently ambiguous with respect to causality” (Goswami, 2015). In addition, the non-linguistic deficit should be specific to reading material to be considered as a possible causal origin of DD (“Sensory processes underlie all childhood learning. Therefore, evidence of putative sensory deficits that affect only reading is not persuasive” Goswami, 2015). Our hypothesis was that there is, in some dyslexics, an impairment that lies neither at the primary sensory or oculomotor level nor at the representational/phonological coding level. It would rather lie at the level of common visual-attentional resources used for simultaneous visual processing. These resources are shared for spatial binding of letter-like symbols and for extending the spatial window of processing over visual arrays. Consequently, only condition that involve simultaneous processing of multiple symbols (made up themselves of multiple strokes) requires spatial integration both within and between object. Such a condition is seldom in everyday life but is systematically encountered during reading acquisition, until visual recognition of letters and words as single-units is acquired. Indeed, reading material is made of multiple symbols, which represent phonological codes, but this might not always be what is problematic in DD. Symbols are also spatially specific combinations of strokes (that sometimes differ by only one line) and this is what defines them in the visual search experiment and distinguishes them from filled objects that are more likely to be processed as single perceptual units (Palmer & Rock, 1994). Poor readers have already been shown to be slow specifically in visual search involving symbols, whether they are alphanumeric or not (Casco & Prunetti, 1996). Such specific visual difficulty in processing multiple written symbols could, therefore, be hypothesized to produce VA profile of DD. However, it remained to be tested whether this specific slowness in symbol visual search is related to the reduced SPL-based ability to extend visual attention over visual arrays, both established by neuroimaging in some dyslexics (Liu et al., 2022; Lobier, Peyrin et al., 2012; Lobier et al., 2014; Peyrin et al., 2011) and by behavioural assessments of patient with focal bilateral damage (Khan et al., 2016; Valdois et al., 2019; Vialatte, Saleme, et al., 2021; Vialatte, Yeshurun, et al., 2021). Here we therefore wanted to confirm that children with clinical DD diagnosis display slower search times for symbols than normal readers at the group level, and investigate whether those dyslexics displaying slow visual search for symbols (DysSlow group) behave so because of a reduced VA field of processing only when processing multiple symbols. To do so, we contrasted two visual search conditions (symbols versus filled objects) and two visibility conditions (full view versus reduced gaze-contingent search visibility window). We also recorded and compared eye movements during these visual search conditions in the two groups of dyslexics and in normal readers. Finally, we examined other visual deficits that have been observed in children with DD in the literature to check whether they are systematically associated with slow visual search for symbols: the reduced visuo-attentional span of consonants (Bosse et al., 2007; Peyrin et al., 2012), the poor performance on elementary visuo-spatial perception (Pisella et al., 2021) and the bias toward local processing (Bedoin, 2017; Franceschini et al., 2017).

#### 4.1. Visual-attentional window reduction specific for multiple symbol processing

Although we confirmed the results of Casco and Prunetti (1996) in our whole group of children diagnosed with DD, not all dyslexic children were actually slow for symbols. This was expected since most cases of DD are considered to emerge solely from phonological deficits. We, therefore, divided the 52 dyslexic children into two groups according to their visual search performance. Twenty (more than a third of the dyslexics: DysSlow group) actually displayed a RT difference significantly larger than the NormalReader group, while 32 of them (DysFast group) exhibited a RT difference between symbols and filled objects similar to the NormalReader group. For visual search involving filled objects, all groups increased their RTs when we imposed a reduced view with respect to the full view condition. This RT increase demonstrated that the target could always be discriminated further away

than 20° of visual eccentricity among filled objects. This was not observed for visual searches involving symbols in the DysSlow group: only the NormalReader and the DysFast groups increased their RTs in the reduced visibility condition. The DysSlow group, who was slower for the symbols condition in full view, was not affected by a gaze-contingent visibility window of 20° diameter, demonstrating that for these dyslexics the target could not be discriminated among symbols further away than 20° of visual eccentricity. In other words, their VA field was smaller than their visual field when these dyslexics processed symbols; their VA field displayed for symbols in full view was equal to or smaller than 20° diameter. Such a small VA field explains their specific slowness for this type of stimuli: because they process at each fixation a smaller surface than the normal readers, they need more time to explore the whole visual display and find the symbol target. This cannot be due to oculomotor impairment since their visual search involving filled objects was similarly efficient as normal readers with the same number and amplitude of saccades, and the same fixation durations. When they process words, this reduced VA field for symbols would force the child to process only few letters simultaneously at each fixation, leading to slow reading or errors. Neuroimaging studies have established that the SPL is involved in simultaneous multiple-element processing and under-activated in DD (Lobier, Peyrin et al., 2012; Lobier et al., 2014; Peyrin et al., 2011). A similar reduced VA field specifically for symbols has been demonstrated in a patient with bilateral SPL lesion (Khan et al., 2016), and a recent study showed that when symbols were all different, this patient could only process a single symbol at each fixation (Vialatte, Salemmé, et al., 2021). Since reading also involves simultaneous processing of multiple symbols that are all different, one can hypothesize that dyslexics may even process letter by letter, which would prevent them from developing expert reading.

#### 4.2. Visual-attentional deficit and other disorders related to reading

One criticism of the proponents of the phonological theory is that VA deficits reported in DD are probably a consequence of the reduced reading experience on phonological recoding of visual stimuli, or on fine ocular-motor control (Goswami, 2015). However, we found that not all dyslexic children displayed visual deficits and atypical oculomotor pattern even though there is no reason to consider that they would have a different reading experience. Moreover, visual search uses non-verbal stimuli that are randomly organized in space, it does not involve visual-to-phonological mapping (but rather visual feature integration and discrimination Treisman & Gelade, 1980). Note that this is not the case of the global report of letters. Two complementary tasks are recommended by the researchers who developed the EVADYS software (<https://www.happyneuronpro.com/orthophonie/espace-evaluation/evadys/>) to be able to conclude that the failure at the global report task actually corresponds to a VA span deficit, i.e., a reduced amount of distinct visual elements which can be processed in parallel in a multi-element array (Bosse et al., 2007). The Letter Identification Threshold task should be run beforehand: it measures the minimum presentation duration of a unique letter allowing the child to report it verbally. Report accuracy of 80% with a presentation duration of 50 ms is a prerequisite to allow the clinician to interpret the performance on the global report task as a specific VA deficit in processing multiple letters simultaneously (Guidelines of EVADYS). Indeed, the letter identification task, as well as the global report task, can be failed because of a reduced capacity to rapidly access consonants' names or to mobilize enough attention in the short period of letter presentation. If it is the former, it can be linked to impaired knowledge or access to letter names, possibly due to inefficient phonological processing. If it is the latter, it can be linked to a general, multimodal, deficiency of executive functions. The EVADYS software also provides the Partial Report task in which letters strings are briefly flashed as in the global report task, followed by a visual cue indicating a specific location within the string. The child has to report only the letter that was presented at this location. In absence of impairment in this complementary task, impairment at the global report task can be due to a visual or multimodal

short-term memory deficit hindering the maintenance of all the letters perceived in the brief period of visual presentation throughout the verbal report time. This is why the EVADYS software computes an average of the partial and the global report scores and it provides norms for this combined measure. Regrettably, in the present study we did not administer these complementary tasks that could have been useful in clarifying the nature of the fragile global report performance observed in the DysSlow group, as expected, but also in the DysFast group. If we had determined the group of children with VA deficit based on fragile performance on the global report task, it would have been different and larger than our DysSlow group (see individual data on Appendix, Table A2). We can, therefore, only speculate that the global report performance might be impaired due to specific reduced VA capacity in the DysSlow group and due to one of the alternative causal deficits described above in the DysFast group (phonological or executive functions). We wish to argue that the same flaws do not apply to our symbol versus filled object visual search test. The visual search task does not involve a brief duration of presentation which requires the child to mobilize attention efficiently and quickly. Moreover, in the present visual search task, there is no verbal labelling and no memory involved, since no report is requested, the target is always the same and our symbols clearly have no representational value. Therefore, we can conclude that, for VA dyslexics, symbols of the written languages are problematic because of their typical visual complexity. Integration of written symbols and then of written words in stored memory (orthographic lexicon), such that they can automatically be recognized as familiar visual objects, would consequently require a lot more time and effort, suggesting new approaches for early detection and efficient prevention of VA dyslexia. The specificity of the impairment for symbols in our DysSlow group of dyslexic children thus provides the requested explanation of why such deficit in the visual domain would only affect visual activity involving stimuli made of combined separable features, like letters. It also distinguishes VA dyslexia from a more general deficit of attention and executive functions because this would also impair visual search for filled objects and the general ability to perform visual search with a reduced visible window. In this respect, a child with VA dyslexia has a profile that stands in contrast with the profile of a child with attention deficit hyperactivity disorder. Note also that the explanation of the difference between our symbol and filled object conditions cannot be that for the “filled figures” the vertical line is slightly thicker and more visible, nor that symbols require more fine-grained visual analysis, because the task is a feature-absent search, and thus does not consist of detecting a feature but rather of detecting the shape that is missing something. One could even predict that with filled objects, the distracters would be more salient, or simply that there is more distracting information. The exploratory eye movement pattern of children with DD has also been studied during reading or reading-like conditions. It is sometimes considered to be a consequence of poor reading experience or, on the contrary, to be a primary cause of DD (e.g., Pavlidis, 1981). Our study of the ocular parameters during visual search demonstrated that atypical ocular behaviour can neither be a primary oculomotor deficit nor a consequence of poor reading experience, since it appeared specifically when processing symbols in a specific group of individuals with DD. The divergent ocular profile of these individuals with DD could moreover be qualitatively mimicked in normal readers, in terms of increased fixation time and number of saccades, by artificially reducing their window of visual processing. The behaviour of the dysSlow group was not quantitatively mimicked because the natural size of the VA field of the DysSlow group was even smaller than 20°. Saccade amplitude was reduced in all groups in the condition of artificial visibility reduction where they were conscious of their reduced field of view. However, it was not the case for the DysSlow group in the full view condition despite the natural reduction of their useful field of view. This highlights that dyslexics suffering from natural VA capacity reduction would not be conscious of it. They may instead have the illusory perception that they can process symbols as well as other objects throughout their whole consciously perceived visual field. We speculate that they, therefore, would not adapt their exploratory eye movement

amplitude to their reduced processing field when processing symbols, and would have to compensate with more numerous saccades and longer fixation duration in order to process the whole visual display with their useful field of view and find the target. To sum up, showing similar abnormal eye movement pattern emerging in DD when processing symbols and in normal readers when processing in a smaller spatial window, the present results suggest that a fine ocular-motor control deficit cannot be considered as causing abnormal exploratory eye movements, at least not in all cases of DD. Instead, an atypical ocular profile appears to be a consequence of visual processing capacity reduction (Prado et al., 2007). A reduced attentional window specific to symbols (rather than a primary oculomotor impairment) can be put forward as one of the possible causal factors hindering reading acquisition. This specific deficit evidenced in visual search would more generally correspond to the impairment of simultaneous visual processing already documented in the literature and attributed to dorsal visual stream (or SPL) dysfunction (Bedoin, 2017; Lobier, Peyrin et al., 2012; Lobier et al., 2014; Lobier & Valdois, 2015; Peyrin et al., 2012; Pisella et al., 2021; Valdois et al., 2019; Vialatte, Salemme, et al., 2021).

#### 4.3. Visual-attentional deficit and other visual tasks

Individual data (Appendix, Table A1) showed that only five children in the whole sample of dyslexics (16%) displayed an asymmetry index significantly smaller than the NormalReader group in the local–global shape identification task. This might be due to the large standard error of our control group in this task. Interestingly, the five children exhibiting this deficit were all in the DysFast group. This may be due to our choice to use filled objects (as in Franceschini et al., 2017) in order to isolate a potential global attention deficit from the consequences of a reduced VA field specifically when processing symbols. In such case, we would hypothesize a consistent local bias in the DysSlow group, due to their reduced VA field for symbols, if we had used stimuli made up of empty shapes as in Bedoin (2017). It can also be mentioned that, as was the case for the global report task, the local–global shape identification task involves a brief duration of presentation which requires the child to mobilize attention efficiently and quickly. Individual data (Appendix, Table A3) showed that one-third of the whole sample of dyslexics displayed a total score below the interquartile range of their age category (norms published in Pisella et al., 2020) at the EVSP screening test, which is a lower prevalence than observed in the group of Specific Learning Disorder (including DD and/or dyscalculia) in Pisella et al. (2021), but most of them were in the DysSlow group. More precisely, half of the individuals in the DysSlow group scored below the interquartile range of their age category in the subtests of Midline judgement (involving a horizontal line and a vertical crossing mark) and Position selection (involving to compare spatial relationships of symbols made of dots within a square), tasks that required processing of multiple elements simultaneously in a large VA field. At individual level, the consistency across the different visual behavioural tasks of the present study is thus not satisfactory, especially if one considers the results of the global report task when used as a single measure of the VA span. Further research is, therefore, needed to determine whether there are distinct and dissociable VA processes impaired in DD, as is the case for phonological processes (frequent dissociation between phonological span and measures of phonological awareness for example in our sample as can be seen on Appendix, Table A2). However, at group level, the results of the present study were in accordance with our predictions at least for children in the DysSlow group: they were also impaired in the letter string global report task and in the EVSP test, but did not display more local interference than controls in our local–global shape identification task involving small filled shapes.

#### 4.4. Relevance of our visual search task to clinical practice (VA deficit diagnosis, early detection and remediation)



We have argued that our visual search task allows for more straightforward VA interpretation compared with other visual tasks because its performance is unlikely to be affected by language skills and executive demands. This is what would make it useful for diagnosing a VA deficit in DD children. Note that this does not exclude the independent presence of phonological disorders. Saksida et al. (2016) rarely found the VA span deficit in isolation from phonological deficits in their sample of DD. Here (Appendix, Table A2), almost all dyslexics of the DysSlow group exhibiting VA span deficit showed it in isolation from phonological span deficit, when tested (by syllable repetition). Among the 18 children in this DysSlow group who shared their clinical record, 15 were tested by their speech therapists on phonological abilities, only 1 was impaired in non-words repetition, 2 exhibited pathological phonological span, but 9 exhibited pathological phonological awareness (tested by phoneme deletion or spoonerism). The current clinical distinction between profiles of DD is still based in France on the ability to read regular words and non-words (that would be pathological in phonological profile) versus irregular words (that would be pathological in VA profile). However, the large population presenting difficulties with both regular and irregular words is wrongly considered as exhibiting mixed (phonological and VA) deficit, since when using phonological awareness tasks on the one hand, and a measure of the VA span on the other hand, more than 60% of this population exhibit a single (phonological or VA) deficit (Zoubrinetzky et al., 2014). The present results further suggest that, not only regular words, but also non-words reading deficit is not characteristic of phonological deficit, since it was observed in 12 among the 17 children of the DysSlow group whose data was available on this test. The efficiency of a training involving letter visual search among symbols has been demonstrated to improve reading accuracy in a group of children with DD (Vialatte et al., 2023). We speculate that when a symbol (letter) becomes familiar enough, it can be processed as a single unit, therefore lead to less spatial binding errors (visual confusions) and facilitate letter strings (words) processing. Such training would be even more relevant in kindergarten, when the child is faced for the first time with reading materials, in order to automatize visual recognition of letters in cluttered environment. The literature focuses on the SPL as neural substrate related to VA deficit, and the SPL has increased connectivity with the region of the visual word form area (VWFA) at the early stage of reading acquisition (Cohen & Dehaene, 2004; Moulton et al., 2019). This suggests a crucial role of the SPL in the specialization of the VWFA, hence in the normal development of visual recognition of letters, graphemes and words. Being easily administered in pre-literate, our symbol versus filled object visual search task would be useful in this context for detection of a risk to develop visuo-attentional dyslexia, allowing for early and specific remediation.

## 5. Summary and conclusions

Correlatively to slow performance in symbols visual search, we have demonstrated reduced VA field in a group of dyslexics. This task requiring no letter knowledge, no verbal labelling and no reading ability, we have argued that this reduced VA capacity cannot be connected to any phonological deficit or any lack of reading experience. This reduced VA field can nevertheless cause a deficit specific to reading since it is observed only when processing multiple visual stimuli made of combined separable strokes (symbols) like letter strings. This VA shrinkage would prevent the child from processing a whole word, and storing it into the orthographic lexicon. The present results have theoretical relevance both regard the causality of a VA deficit for DD and the role of SPL-based VA resources in normal visual processing. They provide arguments that extending the spatial focus of attention over visual arrays shares common resource with spatial binding of separable features. On the one hand, such common resources would explain how object and spatial attention interact and especially how visual complexity affects spatial attention in normals (Khan et al., 2016; Young & Hulleman, 2013). On the other hand, such functional sharing would explain that the processing of

multiple symbols would be a particular burden for a person with reduced VA resources and, therefore, that this person would be specifically impaired in reading.

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# Response time

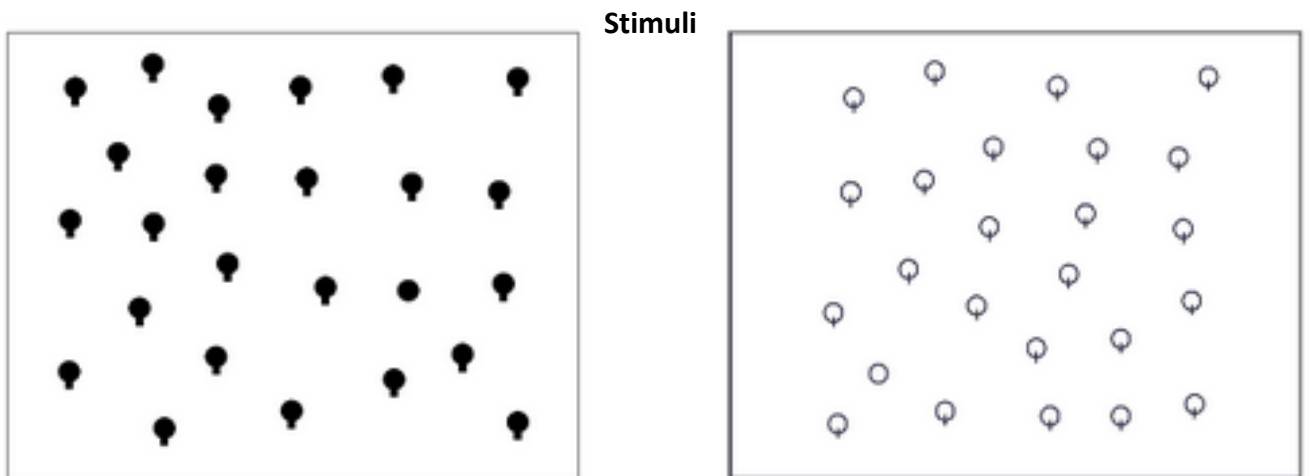
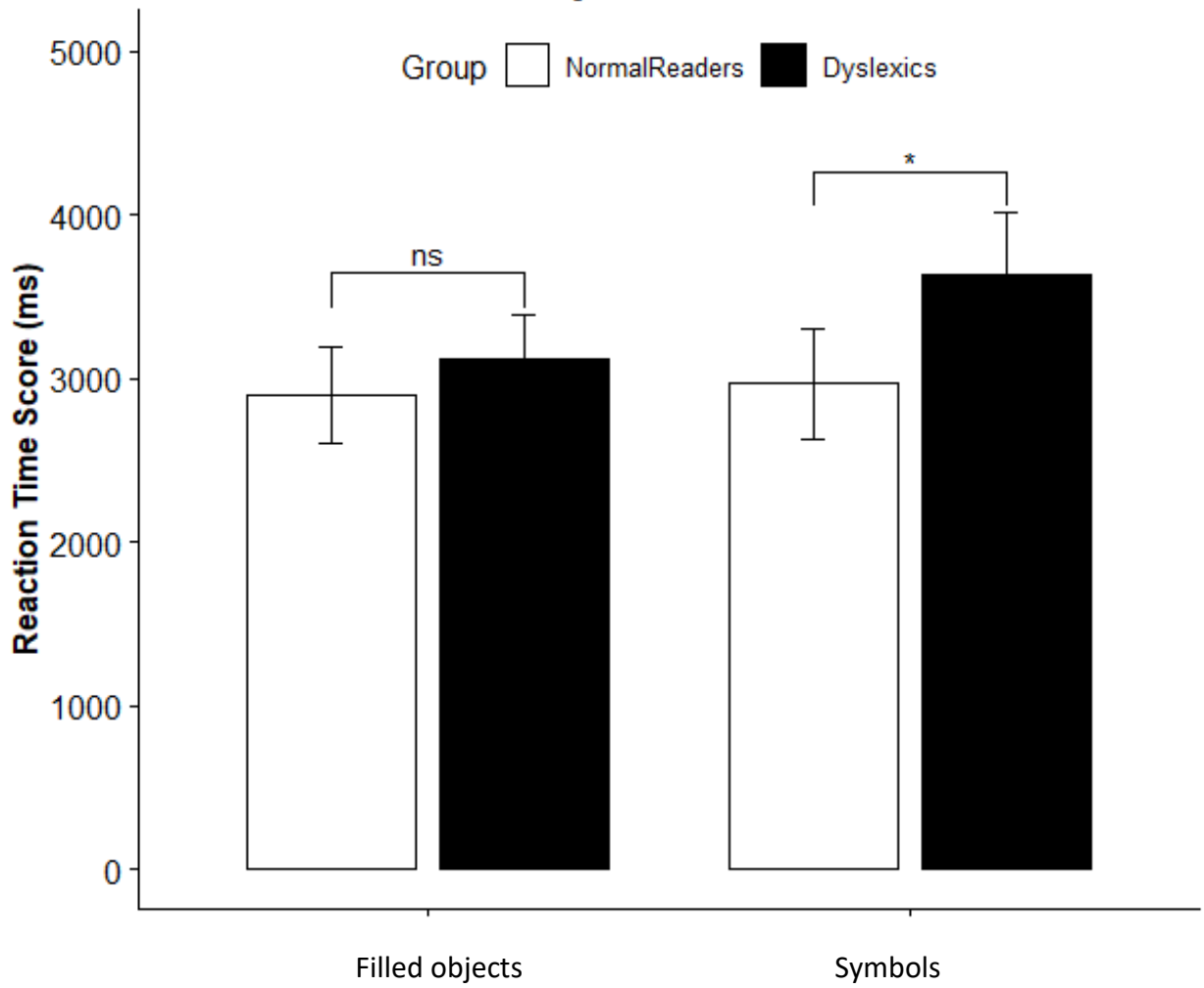


Figure 1



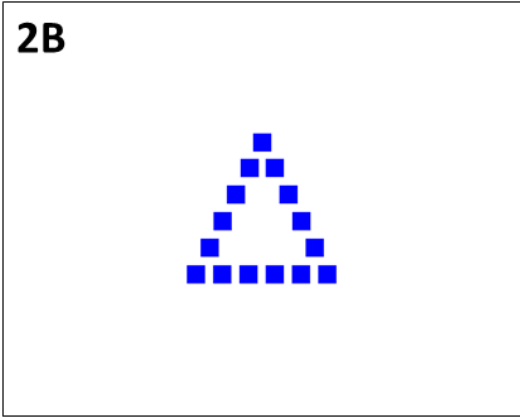
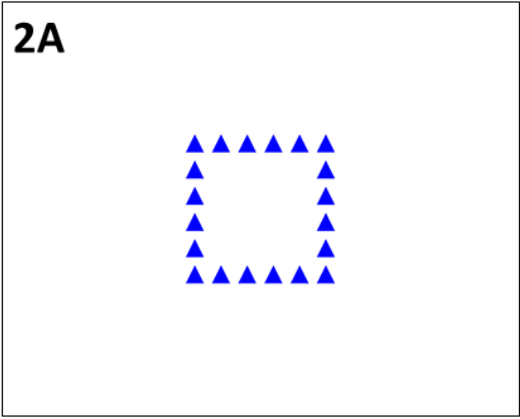
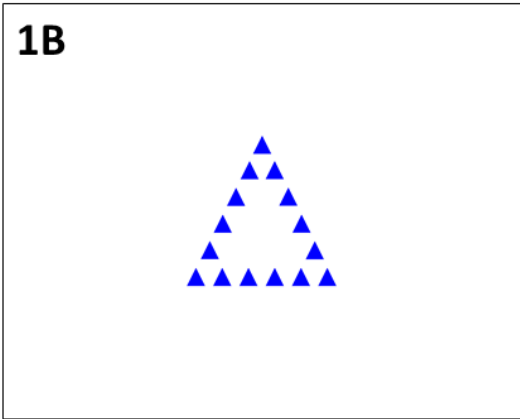
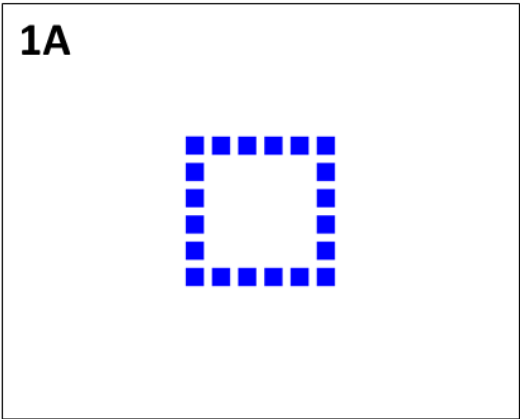


Figure 2

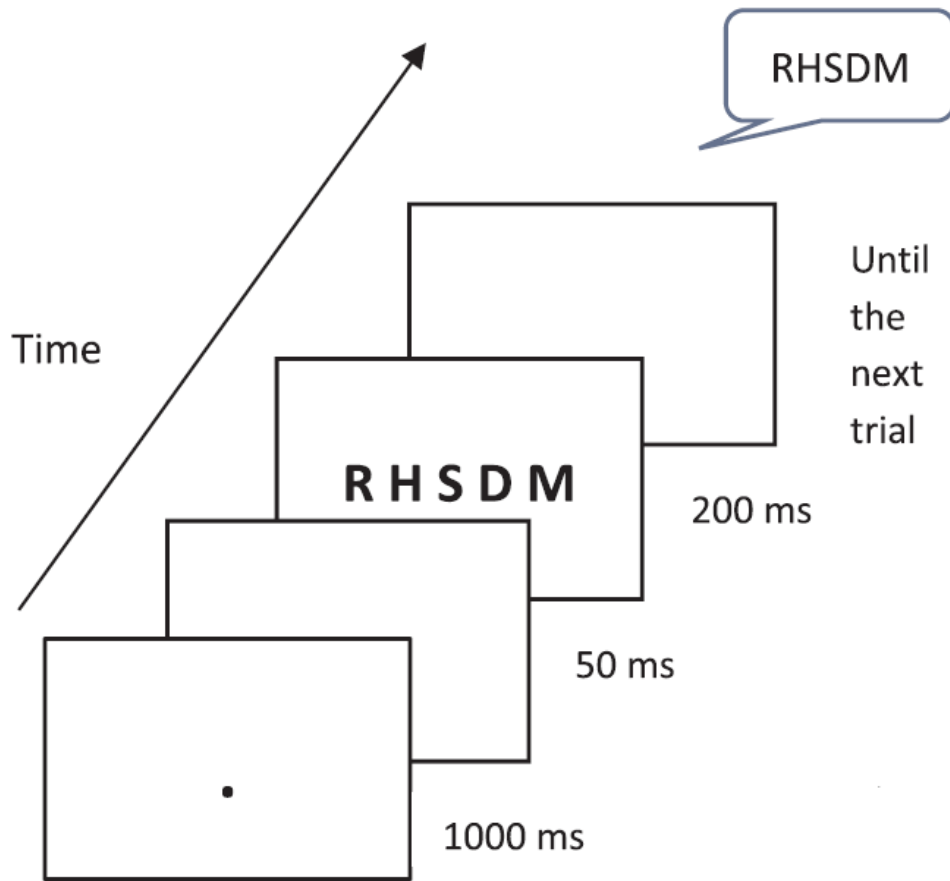


Figure 3

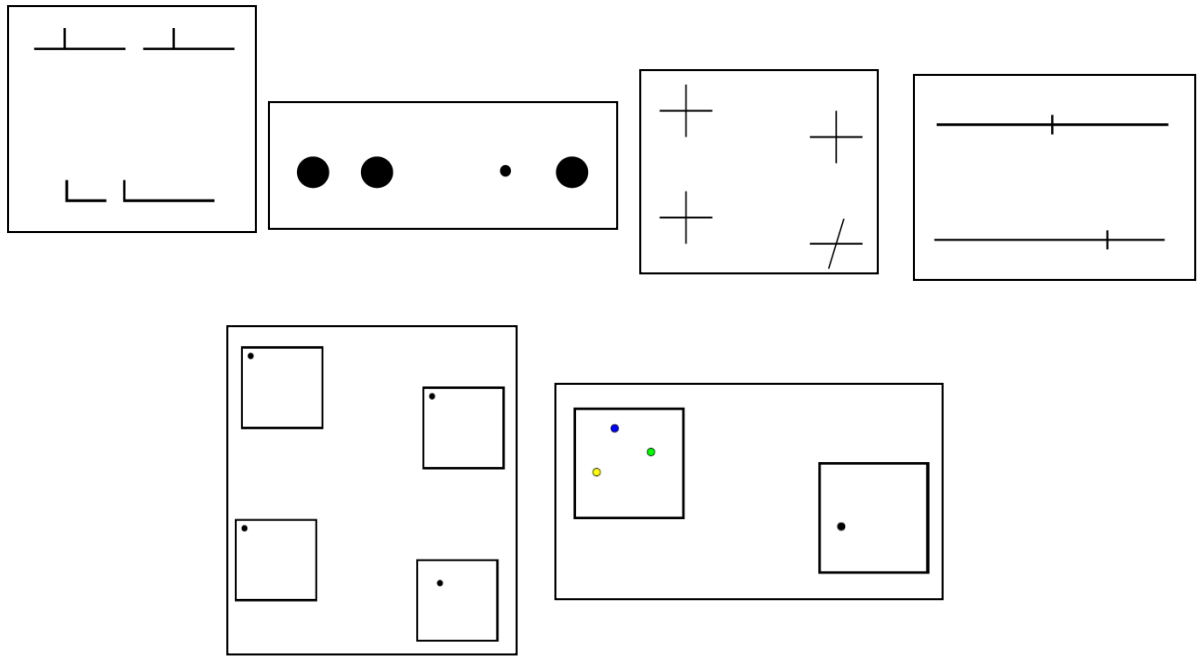


Figure 4

RESPONSE TIME (ms)

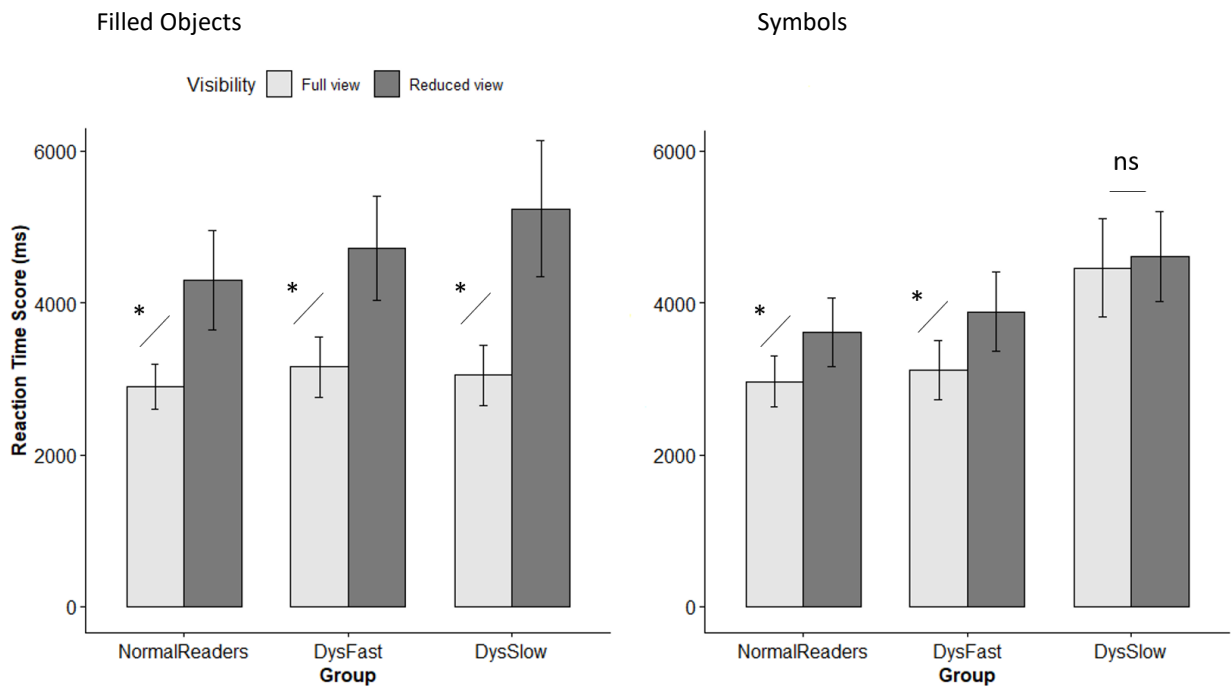
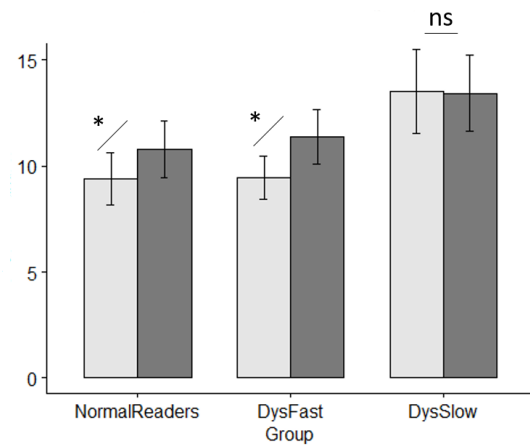
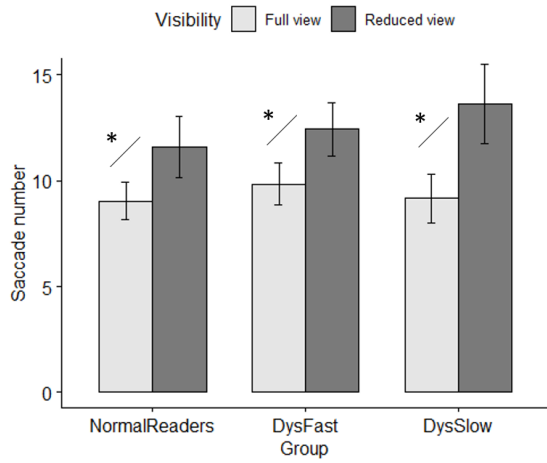


Figure 5

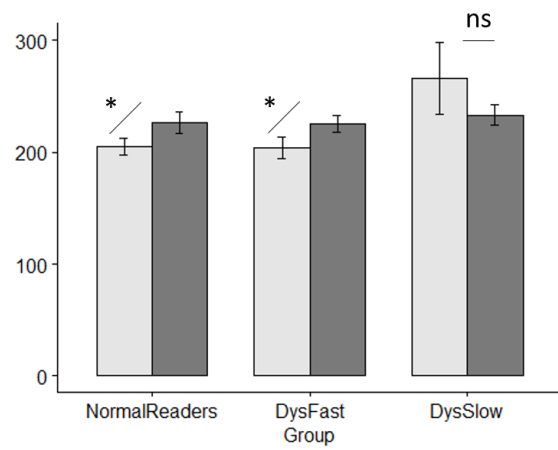
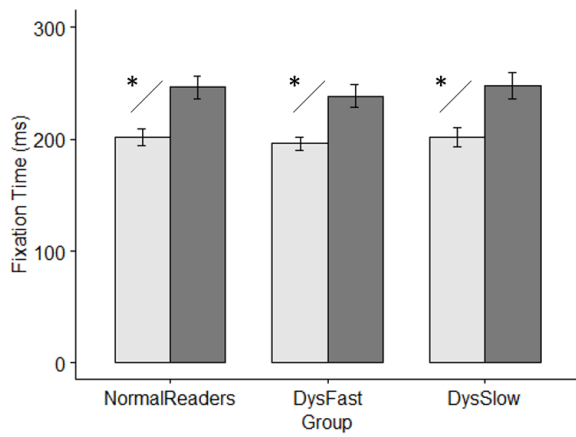
Filled Objects

Symbols

A : MEAN NUMBER OF SACCADES



B : MEAN FIXATION TIME (ms)



C : MEAN SACCADE AMPLITUDE (°)

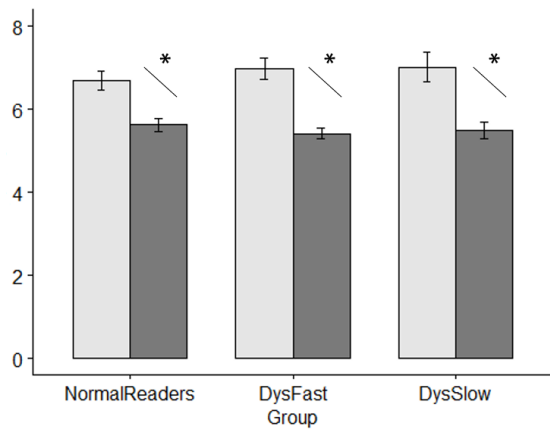
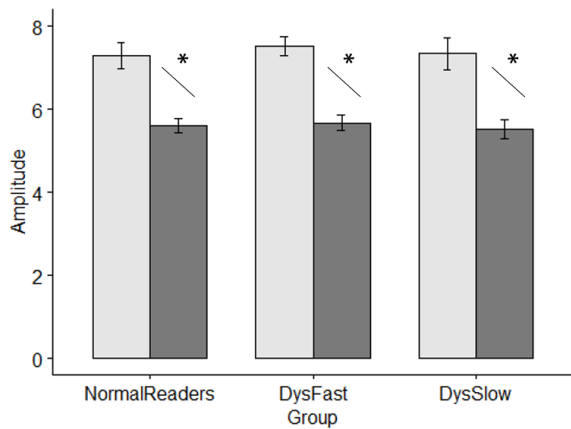


Figure 6

## Figures captions

**Figure 1:** Mean response time of normal readers (light grey bars) and children with DD (dark grey bars) while performing visual searches with two types of stimuli: filled objects or symbols (examples of visual displays are depicted). Error bars represent the confidence interval of the groups. \* $p < 0.05$ ; ns: not significant

**Figure 2:** The four visual displays of the local-global attention task. Top row pictures are congruent stimuli, and bottom row pictures are incongruent stimuli.

**Figure 3:** Illustration of the global report task to measure the VA letter span.

**Figure 4:** Illustration of the six subtests of the elementary visuo-spatial perception (EVSP) screening test. Length comparison (T1), Size comparison (T2), Angle comparison (T3), Midline judgement (T4), Dot-square Position comparison (T5) and Dot-square Position Selection (T6). For T4, subject had to respond yes/no, an example of mark at midline is illustrated on top and an example of mark not at midline is illustrated below. For T6, subject had to select the colored dot in the left square that matches the position of the dot in the right square. For the other subtests, examples of “same” and “different” trials are illustrated above and below, respectively. Each of the six subtests included 12 trials. Six “identical” and six “non-identical” image-pairs within each subtest were intermingled pseudo-randomly. The trials whose correct response was “different” (or “not midline” for T4) were presented in order of increasing difficulty. The twelve trials of T6 were presented in order of increasing number of distracters.

**Figure 5:** Mean RT scores for the Filled Objects (where subjects had to find the black disk among filled lollipops, left panel) and for the Symbols (where subjects had to find the circle among lollipops, right panel). In light grey the performance in Full View and in dark grey with a Reduced gaze-contingent visibility window of 20°. Error bars represent the confidence interval of the groups. \* $p < 0.05$ ; ns: not significant.

**Figure 6:** Ocular behavior for the Filled Objects (where subjects had to find the black disk among filled lollipops, left panel) and for the Symbols (where subjects had to find the circle among lollipops, right panel). In light grey the performance in Full View and in dark grey with a Reduced gaze-contingent visibility window of 20°. A: Mean saccade number. B: Mean fixation time in milliseconds. C: Mean saccades amplitude in visual degrees. Error bars represent the confidence interval of the groups. \* $p < 0.05$ ; ns: not significant.

|        |  |                                |                              |                                  |                           |  |               |
|--------|--|--------------------------------|------------------------------|----------------------------------|---------------------------|--|---------------|
| Tasks  |  | Symbols -<br>Filled<br>Objects | Visual search<br>exploratory | Effect of<br>gaze-<br>contingent | Global<br>report<br>score | Local -<br>global<br>asymmetry<br>index (ms) | EVSP<br>Score |
| Groups |  |                                |                              |                                  |                           |  |               |

|              | Reading age delay > 18 months (percent of individuals) | visual search index (ms) | eye movements        | window on Symbol search times and oculomotor pattern |                   |               |                  |
|--------------|--|--------------------------|----------------------|--|-------------------|---------------|------------------|
| NormalReader | 0%   | 66.3<br>(387)            | –                    | yes  | 84.45<br>(8.55)   | 25.6<br>(99)  | 62.18<br>(3.1)   |
| DysFast      | 100%   | -35.1<br>(535)           | Normal               | yes  | 71.34 *<br>(10.7) | -17.8 (181)   | 61.03<br>(3.8)   |
| DysSlow      | 100%   | 1415*<br>(719)           | Abnormal for Symbols | No <sup>1</sup>                                      | 73.45 *<br>(11.1) | 56.9<br>(130) | 59.90 *<br>(3.3) |

**Table 1** – Summary of the experimental results for each group. Percentage of children with reading delay >18 months. Visual search: mean difference between mean RT scores in Symbols and Filled Objects conditions in Full View (and standard error), exploratory eye movement pattern, and whether RT and ocular pattern changed in artificially Reduced View. <sup>1</sup> except saccade amplitude. Global report of letters strings: mean total score /100 (and standard error). Local/Global attention: mean interference asymmetry index (and standard error), the lower the index, the more local interference. Elementary Visuo-Spatial Perception screening test: mean global score /72 (and standard error). Asterisk indicates significant difference compared to the NormalReader group performance.

