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ABSTRACT

Whether eye-movements deficits are causal in reading disorders (RD) or rather a consequence of linguistic processing difficulty experienced by disabled readers has been extensively debated. Since RD are frequently comorbid with the Neurofibromatosis type1 (NF1), children with NF1 were used as a comparison group for children with dyslexia in this study. Eye movements were recorded while 21 dyslexic, 20 NF1, and 20 typically developing children performed an oculomotor lateralized bisection task. In this experiment, we manipulated the type of stimulus - discrete (words and strings of hashes) versus continuous (solid lines) - and the visual field where the stimulus was displayed (left vs. right). The results showed that (1) only proficient readers (TD and NF1 without RD) showed fully developed oculomotor mechanisms for efficient reading, with a clear preferred viewing location located to the left of the word's centre in both visual fields, and fine-tuned saccade targeting guided by the between-character space information and (2) NF1 poor readers mirrored the dyslexic eye movement behaviour, with less accuracy and more variability in saccadic programming, no sensitivity to the discreteness of the stimuli, particularly in the left visual field. We concluded that disruption to oculomotor behaviour reflects the fact that many of the processes involved in reading are not yet automatized for children with RD, independently of NF1. This suggests that the differences in saccade targeting strategy between children with and without RD would be secondary consequences of their reduced reading experience.

KEYWORDS. Saccadic computation; Reading experience; Developmental dyslexia; Neurofibromatosis type 1; Parafoveal processing.

ABBREVIATIONS.

DD	Children with developmental dyslexia
ILP	Initial landing position
LVF	Left visual field
NF1	Neurofibromatosis type 1
NF1RD	Children with neurofibromatosis type 1 with reading disorders
NF1noRD	Children with neurofibromatosis type 1 without reading disorders
PVL	Preferred viewing location
RAN	Rapid Automatized Naming
RD	Reading disorders
RVF	Right visual field
TD	Typically developing children
VP	Viewing position

1. INTRODUCTION

As reported by several studies, many adults with dyslexia or poor reading skills experienced early reading difficulties (Eloranta et al., 2018; Smart et al., 2017). Indeed, learning to read can be a hard task for some beginners, requiring becoming more efficient in linguistic processing and to gain cognitive control of saccadic eye movements. Understanding the mechanisms underlying reading difficulties has therefore been the focus of ongoing research, with particular interest in the role of eye movements in the learning-to-read process.

Much research has focused on linguistic processing abilities as determinants of individual differences in reading acquisition (e.g., Kim & Pallante, 2012; Landerl et al., 2019; Leppänen et al., 2004). If phonological processing is a necessary (but not sufficient) condition for the development of adequate word recognition skill, our ability to read depends also on visuo-attentional processes and eye movement control (e.g., Bellocchi et al., 2017; Besner et al., 2005; Facoetti et al., 2010; Plaza & Cohen, 2007; for reviews, see Hung, 2021; Leibnitz et al., 2017; Premeti et al., 2022). Reading does require children to focus selectively on words in a left-to-right attentional scanning. The reader's eyes have to learn to land in the best position within the words to be read, extract the relevant information, and program the next saccade (Ducrot et al., 2013; O'Regan & Lévy-Schoen, 1987; Rayner, 1986).

As reading proficiency increases, a child becomes familiar with the printed form of words and changes in eye movement behaviour are observed: the span of effective vision increases (extending asymmetrically in the direction of reading, even in beginning readers; Häikiö et al., 2009; Rayner, 1986), the saccades size lengthens, the fixations duration and the number of refixations decrease (Blythe, 2014; Blythe & Joseph, 2011; Rayner, 2009). Moreover, the role of attention in reading evolves with expertise, i.e., expert readers need less attention to process words than beginning readers (Bellocchi & Leclercq, 2021; LaBerge & Brown, 1989; Leclercq & Siéroff, 2016).

The present study further investigates the perceptual and attentional factors that determine the eyes' landing position in children and whether or not the pattern of eye movements (and in particular the primary saccade landing sites) can provide useful information to help characterize the reading skills in neurodevelopmental disorders. Word length, that is provided by the visually salient extra spacing between words, in most languages that use an alphabetic script, is a primary source of information in order to guide the eyes during text reading and determine where the eyes first land in a word (e.g., Inhoff et al., 2003; Rayner et al., 1998). Rayner (1979) first demonstrated that the landing position in a word during continuous reading, referred to as the "preferred viewing location" (PVL), is usually located halfway between the beginning and the middle of the word for languages read from left-to-right (McConkie et al., 1988; Radach & Kempe, 1993; Rayner, 1979; Vitu et al., 1990). It is thought that the PVL reflects a strategy whereby readers aim to fixate the centre of the word (e.g., McConkie et al., 1988; Reichle et al., 2003; but see Vitu, 2003) and fall short of that optimal viewing position (OVP) (i.e., saccades would undershoot their goal), owing to the properties of the oculomotor system (Engbert & Krügel, 2010; Joseph et al., 2009; McConkie et al., 1988; Nuthmann et al., 2005; O'Regan & Lévy-Schoen, 1987). Alternatively, a visual strategy could be developed to send the eyes to a location that optimizes information uptake from the fixated word (Legge et al., 1997; O'Regan & Lévy-Schoen, 1987). The evidence strongly suggests that in addition to length information, salient orthographic information can be extracted from the parafovea and influence saccade computation (e.g., orthographically unfamiliar initial trigrams, Hyönä, 1995; White & Liversedge, 2006). Furthermore, developmental research suggests that beginning readers do learn to optimize saccade targeting strategies, with average initial landing positions (ILPs) gradually shifted towards the word centre during the first years of formal reading instruction (Ducrot et al., 2013; Huestegge et al., 2009; Joseph et al., 2009; Vorstius et al., 2014). Based

on the dual-route cascaded model of Coltheart et al. (2001), the child would rapidly switch from a grapho-phonological decoding mode (indirect route), with a letter-by-letter processing, to an orthographic treatment mode (direct route) with an OVP for word processing. Similarly, the attention deployed on words would be adapted to the preferred global processing mode (Ans et al., 1998) and would be related to the efficiency of the oculomotor parameters (Prado et al., 2007). Thus, during the first year of learning, oculomotor control and especially the PVL will be adjusted in parallel to the development of an optimal lexical and visual-attentional processing strategy for word reading.

Of particular interest here is the study by Ducrot and Pynte (2002) who used an oculomotor lateralized bisection task and demonstrated that the presence of between-character space information influences saccade programming. According to this view, PVL "is due to attentional processes that develop for any type of discrete stimulus, whether or not reading is actually required" (Ducrot & Pynte, 2002, p. 1142). These authors argued that "linguistic-like" stimuli (i.e., with inter-character spaces) encourage a saccade targeting strategy that takes the direction of visual exploration into account and aims to land left of the centre of targets (for languages read from left to right), in preparation for subsequent left-to-right attentional scanning. Note that this oculomotor strategy is modulated according to the visual field (VF) in which the stimulus is displayed, resulting in a left-right asymmetry in saccade extent which is larger in the left visual field (LVF) than in the right visual field (RVF). In the same vein, Bellocchi et al. (2019) found that the average landing positions of fifth grade typical reading children were left of centre for stimuli with inter-character spaces (words and strings of hash marks) in both the left and right VFs. Interestingly, beginning readers and children with DD were only influenced by the linguistic nature of stimuli such that ILPs were shifted more toward the beginning of the strings only when the stimulus was a word.

Naturally, a reasonable question arises: do children with different levels of reading ability differ in their saccade computation strategies when processing parafoveally presented stimuli? In the present study, we used the oculomotor lateralized bisection task as Ducrot and Pynte (2002) to further investigate saccade programming in typical reading children and children with reading difficulties**,** under conditions that modulate the direction of visual exploration and minimize the influence of linguistic factors.

A huge amount of data has reported differences between the eye movement patterns of dyslexic readers and those of skilled readers. Poor readers and individuals diagnosed as having dyslexia exhibit inefficient oculomotor behaviour while reading, with longer saccades, shorter fixations, and more refixations than typical readers (Ashby et al., 2005; Franzen et al., 2021; Gagl et al., 2014; Gangl et al., 2018; Hawelka et al., 2010; Kirkby et al., 2022; Lefton et al., 1979; Prado et al., 2007; for review, see Rayner, 1998). Also relevant for the present study are experiments reporting a missing parafoveal preview benefit in poor readers or dyslexic children (Silva et al., 2016). The difficulty of pre-processing the word to the right of fixation may affect both saccade-planning and its execution towards the PVL. In that sense, dyslexic readers tend to initially fixate words closer to their beginning than good readers (Gagl et al., 2014; Gangl et al., 2018; Hawelka et al., 2010; Kirkby et al., 2022; McDonald et al., 2006; McKeben et al., 2004). However, there is still some unsettled disputes on the role of these atypical eye movement patterns as a causal factor in dyslexia (see Blythe et al., 2018, asserting that instead they might primarily reflect an underlying difficulty in written word recognition or decoding). Indeed, the attempts to replicate differences in eye-movement patterns of dyslexic, poor and control readers when performing nonreading tasks have been essentially unsuccessful, suggesting that children "with delayed reading skills (identified by an assessment of age referenced reading ability rather than a diagnosis of dyslexia possess the

capacity to execute eye movements equivalent to those with good reading skills" (Hindmarsh et al., 2021, p. 1135).

The point of agreement is that in a reading task, children with DD exhibited atypical visual-processing skills. Among them, the deployment of visual attention seems to be impaired in DD individuals. As mentioned above, several studies have shown that in left-to-right reading systems, the fixation point of skilled readers was often located toward the left of the strings, when they processed multiple characters at once, under the influence of reading habits and experience (e.g., Ducrot & Pynte, 2002; Sireteanu et al., 2005), suggesting a left dominance of attention distribution in the process. DD children have a deficit in RVF attentional inhibition, and their attentional resources can be excessively interfered by RVF information (Li et al., 2021). It results in the ignorance of LVF information (see Facoetti et al., 2006; Hari & Renvall, 2001), which leads to no significant difference between LVF and RVF, showing an unbiased distribution pattern of attention resources (Li et al., 2021). In that vein, Ducrot and colleagues found a symmetric OVP curve for dyslexic readers in foveal vision, contrary to control who demonstrated a typical OVP effect with a left-right asymmetric J-shape curve (Bellocchi & Ducrot, 2021; Ducrot et al., 2003, see also Bellocchi et al., 2019, for a less pronounced left-right asymmetry in parafoveal vision). In addition, children with DD are more affected by visual crowding (even with non-linguistic stimuli, Joo et al., 2018; Spinelli et al., 2002) and benefit more from increased text spacing (Perea et al., 2012; Zorzi et al., 2012; for reviews, see Bellocchi et al., 2013; Gori & Facoetti, 2015). Finally, the atypical eye-movement patterns observed in dyslexic children have been linked to impaired visuo-attentional processing, and poor visual attentional span abilities, resulting in fewer letters simultaneously processed and more rightwards fixations (Prado et al., 2007). As suggested by Facoetti (2012), a possible neurobiological substrate of visuo-spatial attention deficits in DD could be a weakened or abnormal magnocellular input to the dorsal visual

stream. Magnocellular–dorsal deficits could lead to reading difficulties through impaired serial attentional orienting (Facoetti et al., 2010; Franceschini et al., 2012; Vidyasagar & Pammer, 2010) or poor eye movement control (Stein, 2001; but see Goswami, 2015; Hutzler et al., 2006, for a different point of view).

One of the main motivations of the study was to examine whether deviant eye movements exhibited by dyslexic readers are a symptom of dyslexia or constitute a more causal impairment. Few studies have explored eye movement behaviour in children with a range of reading abilities that goes beyond dyslexia, using eye tracking during a task preserving the perceptual and oculomotor demands of reading (but removing the higher order processing). Could the inefficient eye movement patterns reported in DD be transposed to a reading deficit in another vulnerable population? To find answers to this question, we focused on neurofibromatosis type 1 (NF1), that is a genetic disease in which a high prevalence of reading deficits has been shown (between 30 % to 80 %; Arnold et al., 2020; Chaix et al., 2017; Hyman et al., 2005), with a profound impact on their academic achievement (Krab et al., 2008). In this neurodevelopmental disorder, visual-processing deficits were also demonstrated (e.g., Hyman et al., 2005; Ribeiro et al., 2012; Vernet et al., 2022) and a first eye-tracking study showed atypicality in the saccadic system (Lasker et al., 2003). Some studies have suggested a delay in the maturation of low-level vision processes in children with NF1 (Lasker et al., 2003; Ribeiro et al., 2012). To our knowledge, no study has investigated the involvement of eye-movement control in the reading difficulties observed in NF1 children.

Summing up, reading is primary a visual task requiring good oculomotor and visuo-attentional skills and in which the initial fixation position of a word plays a crucial early role. With expertise, a left-right asymmetry in VF emerges and the discreteness nature of the word becomes a factor of considerable importance when computing the incoming saccade. Some

findings suggest that in reading disorders, such as DD, there is atypical eye movement control and specifically, the implementation of an inefficient saccade targeting strategy. To our knowledge, very few studies have examined the factors that lead to this ineffective strategy in children with severe reading difficulties, either in DD or in NF1. Thus, we assume that it is crucial to better understand the determinants of eyes' landing position in pathological reading in each of these populations. Here, we examined whether children with reading disorders (RD) differed from typical developing readers in saccade targeting strategies, and whether lateralized presentation would differently impact saccade programming in children with and without RD. We hypothesized that if a detrimental effect of LVF presentation is observed, this effect may occur especially for children who have not yet fully developed oculomotor mechanisms for efficient reading (i.e., DD and NF1 children; Bellocchi et al., 2019; Ducrot & Grainger, 2007; Nazir, 2000). Moreover, according to Ducrot and Pynte (2002), we predicted that if landing positions are an indicator of the development of reading skills, ILPs would differ according to stimulus type and reading experience, with only experienced readers being able to take account of the presence of between-character space information to compute saccades. To test this hypothesis, we manipulated the type (linguistic vs. non-linguistic) as well as the discreteness (stimuli with inter-character spaces vs. continuous lines) of the stimuli.

We conducted a three-step analysis. With the first analysis, we investigated the extent to which attentional factors, stimulus features, and reading ability influence eye behaviour, and more specifically the PVL effect in parafoveal vision. At the same time, we explored possible visual and oculomotor deficits in children with DD. The second analysis aimed to quantify the use of different saccade targeting strategies and closer understand their relationship to reading abilities, by comparing NF1 children with and without RD. Finally, a third analysis including all children was carried out, in order to further investigate the relation between individual

landing position and reading skills. We wanted to know if independently of the clinical diagnosis, reading ability only can reveal different saccade targeting strategies.

2. METHOD

2.1. Participants

Twenty typically developing children (TD, 10 females), 21 children with DD (8 females), and 20 children with NF1 (13 females) participated in the present study.

The inclusion criteria were the same as those described in the study by Vernet et al. (2022). All children were between 8 and 12 years old and attended school from grades 2 through 6. They were all French native speakers, right-handed and presented normal or corrected-to-normal vision. There were no significant differences between groups for chronological age (TD mean age = 118.30 months, SD = 11.48; DD mean age = 120.90 months, SD = 14.18; NF1: mean age = 121.57 months, SD = 18.68). All children underwent a complete medical and neuropsychological screening. Children were excluded from the study if they had Attention Deficit Hyperactivity Disorder (i.e., more than 6 symptoms of Hyperactivity and/or Inattention in a parent rating on the DSM-5 diagnosis criteria), intellectual disability (i.e., WISC total IQ below 70 and/or standard score below 7 on the Similarities and/or Picture Concepts subtests), neurological or psychiatric disorder (e.g., epilepsy, brain tumor, or autism), or a known hearing impairment.

For the DD children, the reading level was controlled to ensure that children exhibited reading disorders (i.e., scores at least 1 SDs below the mean on the reading speed and accuracy indices of the Alouette test (Lefavrais, 2005) and at least 1.5 SDs below the mean on the ODEDYS-2 test (Jacquier-Roux et al., 2002)). The reading level was also assessed in the TD group to verify that they were all typical readers (i.e., scores at least superior to -0.5 SDs

on the Alouette-test (Lefavrais, 2005) and on the ODEDYS-2 test (Jacquier-Roux et al., 2002)). As expected, statistical analyses revealed that the DD group displayed significantly poorer performances than the TD group for the three reading indices with large effect sizes [reading age: $t(39) = -10.022$, $p < .001$, $d = -3.131$; reading accuracy: $t(39) = -5.703$, $p < .001$, $d = -1.782$; reading fluency: $t(39) = -11.277$, $p < .001$, $d = -3.523$].

For the NF1 children, participation was offered to all children who met the clinical diagnostic criteria for NF1, according to the Neurofibromatosis Conference Statement (National Institutes of Health, 1988). The reading level was systematically assessed but was not used as an inclusion criterion for this specific subject.

The French ethics committee Review Board approved the study (2014-A01239-38 and 2014-A01960-47), which was conducted according to the guidelines of the Declaration of Helsinki (World Health Organisation, 2008). The written informed consent was obtained from every participant and their legal tutors prior to inclusion in the study. Note that this study included participants from a larger study examining procedural learning and memory[1].

2.2. Material

Oculomotor lateralized bisection task. The material consists of 3 lists of stimuli: solid lines, strings of hashes and words. Each list is composed of 20 items of 5 or 6 characters long. We selected a set of words from the first-grade lemma lexicon of the Manulex database (Lété et al., 2004) that provides reliable information on grade-level word frequency. Half of the targets were high frequency words, with average printed frequency of 419 occurrences per million and the other half were low frequency words (printed frequency of occurrence of 16 occurrences per million). Stimuli were displayed in either the LVF or RVF relative to the

[1] DYSTAC-MAP cohort (ANR-13-APPR-0010)

initial fixation point. The distance between the item and the fixation cross was set at 1.25° from the end of the stimulus when displayed in the LVF or from the beginning of the stimulus when displayed in the RVF. To sum up, two factors were manipulated: (1) the type of stimulus with 3 conditions (i.e., words, strings of hashes and solid lines) and (2) the visual field with 2 conditions s (i.e., LVF and RVF).

Visual-processing skills assessment. The *Developmental Eye Movement* (DEM) test (Garzia et al., 1990) is commonly used to assess visual-processing skills. It consists of reading aloud vertically and horizontally organized digits printed on three different sheets of paper (Test A, B and C). Children were instructed to read aloud the digits as fast and as accurately as possible. This test provides three main indices: (1) the vertical reading time (VT, in seconds) that represents the sum of the time spent on naming the vertically organized digits of Test A and B; (2) the adjusted horizontal time (HT, in seconds) that represents the adjusted time required for reading the horizontally organized digits presented in the Test C; and (3) the total number of errors, which gives the accuracy on the execution of Test C.

Reading skills assessment. One of the most widely used French reading tests for assessing reading efficiency in children is the *Alouette test* (Lefavrais, 1967, 2005). In this test, the child is asked to read a 265-word text passage aloud as quickly and accurately as possible, within 3 minutes. The text consists of real words in syntactically correct but semantically poor sentences. The Alouette test provides three main indices: reading age, reading fluency, and reading accuracy.

2.3. Apparatus and procedure

All children were recruited at both the Hospital of Aix-en-Provence and the Timone University Hospital (Marseille). They were seen individually during two sessions of approximatively 1 hour and a half each. The first one was conducted directly at the hospital

and was intended to verify the inclusion criteria. This session included also neuropsychological assessment with the evaluation of reading level. The second session was carried out at the laboratory to perform the oculomotor bisection task. All children were tested individually in a quiet, separate room. The lighting in the room was adjusted to a comfortable level for each participant and each task.

Some of the following detail is taken from Ducrot et al. (2013). For the oculomotor lateralized bisection task, the eye movements were recorded by a mobile infrared, head-mounted eye tracker (Eyelink 2, SR Research Ltd., Canada). The recording was based on infrared-light reflection from the pupil and cornea of the right eye at a sampling rate of 250 Hz and a spatial resolution of less than 0.04°. A chin-and-forehead rest was used to minimize head movements.

Before the experiment, a calibration step of the eye tracker was performed according to a 9-point grid extended to the whole computer screen. The eye tracker was connected to a Dell D-type docking station and a Dell Latitude D600 laptop computer for data recording and stimulus delivery. The stimuli were displayed in white lowercase letters against a black background in 22-point Courier New font, using a 14-inch colour monitor, at a resolution of 1400×1050 pixels. Participants were seated in front of the screen at 60 cm. At this distance, one letter subtended a visual angle of 0.38° and 1° is equal to 0.95 cm. The space between letters was 1 mm that corresponds to 2.8 pt or 0.09°.

Each trial consisted of the following sequence of events (Figure 1). First, children were required to maintain fixation on the cross in the centre of the screen. Note that the experimenter repeatedly reminded the child to fixate the cross and not to move their eyes away from this point. Five-hundred ms after, the central fixation point was replaced by a parafoveal target displayed in the RVF or the LVF of the fixation point. Therefore, the children were instructed to “move their eyes, as quickly and accurately as possible, to the

position they considered to be the middle of the item" and then validate this position by pressing a button. After the response, the screen was cleared for the next trial that started 500 ms later. Participants performed 12 practice trials beforehand.

[Insert Figure 1 About here]

2.4. Data analysis

The Emaa software package (Ducrot et al., 2006) was used to analyze the eye-tracking data. Trials were excluded from the analysis when an eye-tracker sampling error or a blink occurred during stimulus presentation. We also excluded trials when the saccade latency was shorter than 80 ms or longer than 800 ms (4.3%), the average eye position before saccade onset deviated from the fixation cross by more than ± 0.5 characters (2.9%), or the participant took more than 5000 ms before pressing the button (6.8%).

We used the same eye-movement measures as Ducrot et al. (2013): (1) the saccade latency which is the time between the onset of the target and the beginning of the saccade, (2) the saccade size which is the size of the initial saccade, and finally (3) the refixation probability which is the probability of making an additional fixation within the word before leaving it. To study PVL effects, we also computed (4) the initial landing position in the stimulus. This last parameter is used to determine the landing frequency at each position of the item. Saccade latency was reported in milliseconds, whereas saccade size and initial landing position were expressed in number of characters. For all the variables measured, means were calculated for each participant in each condition.

2.5. Statistical analysis

A three-step analysis was conducted. A first analysis was conducted to examine saccade targeting strategies of children with and without DD in parafoveal vision. ANOVA were

performed with a 2 Visual Field × 3 Type of stimulus × 2 Groups of children model. All factors except the group of children were within-participant variables. Further analyses were carried out in each group independently with statistical a priori comparisons.

In a second analysis, the same ANOVA were performed within the NF1 group, to better understand the factors that determine the saccade targeting strategy implemented by children with RD. Based on their performance on the Alouette test, NF1 children who presented reading disorders (i.e., NF1RD; at least 12 months delay in reading age on the Alouette test compared to chronological age) were compared to NF1 children without reading disorders (i.e., NF1noRD). Note that 11 children were included in the NF1RD group and 9 in the NF1noRD group. The two groups differed significantly in terms of reading age [$t(18) = -4.435$, $p < .001$], reading accuracy [$t(18) = -4.144$, $p < .001$] and reading speed [$t(18) = -5.218$, $p < .001$] [2].

Finally, a final analysis including all children was carried out to further investigate the relation between individual ILPs and reading skills. Each child was assigned an ILP index (their initial-landing position for words in the RVF) and a reading level index (their reading age). The correlations between these two measures were tested. Then, cluster analyses were conducted. The ILPs were analysed by interactive partitioning (K-means), minimizing the within-cluster variability and maximizing the between-cluster variability, with a three-group solution.

3. RESULTS

3.1. Comparisons between children with and without DD

[2] There were no significant differences between the two groups for the chronological age [$t(18) = -5.316$, $p > .05$] and the handedness ratio ($\chi 2 = 0.669$, $p > .05$).

[Insert Table 1 about here]

3.1.1. Saccade Size

The median amplitude of left-to-right saccades in TD children was 3.46 characters, while that of dyslexics was 3.49. For right-to-left saccades, however, we observed a shift of the saccade's distribution toward shorter amplitudes for DD children (as compared to TD children,(3.7 and 4.1 for DD and TD children, respectively). The analysis of incoming saccade size yielded a significant interaction between stimulus type and side of presentation [$F(2,76) = 12.505$, $p < .001$, $\eta_p^2 = 0.247$] and three-way interaction between the group (TD vs. DYS children), the type of stimulus (words, strings of hashes and solid lines), and the presentation side (LVF vs. RVF) [$F(2, 76) = 3.423$, $p = .038$, $\eta_p^2 = 0.080$]. Separate analyses for TD and DYS children indicated that the interaction between the stimulus type and the presentation side was significant in the two groups [$F(2,38) = 7.128$, $p = .002$, $\eta_p^2 = 0.273$ and $F(2,38) = 8.509$, $p <.001$, $\eta_p^2 = 0.309$, for the TD and DD children respectively].

As can be seen in Table 1, for TD children, initial-saccade extent was equivalent in size for all stimuli composed of discrete elements (words and strings of hashes), but was different for continuous solid lines. Pairwise comparisons revealed that the difference between words and strings of hashes was nonsignificant [$F(1,38) = 1.089$, ns] and that the stimulus-type by presentation-side interaction result from the strong opposition between discrete stimuli (words and strings of hashes) and continuous stimuli (solid lines) [$F(1,38) = 8.413$, $p < .01$], thus confirming the influence of stimulus discreteness vs. continuousness in determining ILPs (see Ducrot et al., 2002, for similar conclusions).

For DD children, pairwise comparisons revealed that the stimulus-type by presentation-side interaction was entirely explained by the strong opposition between linguistic stimuli (words) and non-linguistic stimuli (strings hashes and solid lines) [$F(1,38) = 10.208$, $p < .01$], and no difference between strings of hashes and solid lines [F

401 < 1]. As Table 1 shows, DD children do tend to initially fixate *words* at a point somewhere
402 between the beginning and the centre of the target when the saccade was rightward and closer
403 to the word middle for left presentations. For non-linguistic stimuli, however, the mean ILPS
404 were approximately symmetrical in the left and right VFs.

405 **3.1.2. Latency**

406 As first raised by Radach & McConkie (1998), this variable is "of particular interest,
407 because it provides a link to temporal aspects of eye movement control that may well
408 significantly modulate spatial saccade parameters" (p. 83). The ANOVA yielded a main effect
409 of type of stimulus [$F(2,78) = 92.602$, $p < .001$, $\eta_p^2 = .704$], regardless of the presentation side
410 (left or right). Pairwise comparisons revealed that the interaction was due to the difference
411 between discrete and continuous stimuli [183 ms for discrete stimuli vs. 220 ms for
412 continuous stimuli, $F(1,78) = 578.436$, $p < .001$]. The difference between words and strings of
413 hashes was nonsignificant [$F(1,78) = 1.35$, ns]. Note that strings of hashes are letter-like and
414 similar in visual complexity to letters, so processing these symbols might activate a decoding
415 process similar to processing text. Strings of hashes also differ substantially from solid lines
416 in shape, size and brightness. A similar tendency in expert readers has already been observed
417 by Ducrot and Pynte (2002), with shorter latencies in the discrete condition than in continuous
418 condition (173 vs. 193 ms, $p = .06$, Experiment 3). There was also a main effect of group
419 [$F(1,39) = 4.839$, $p = .034$, $\eta_p^2 = .110$] and a stimulus type × group interaction [$F(2,78) =$
420 6.274, $p = .003$, $\eta_p^2 = .139$], showing that latencies were longer for DD children (207 ms, SD
421 = 31) than for TD children (196 ms, SD = 20.5) (see Bucci et al., 2008; Fischer & Weber,
422 1990; Pirozzolo & Rayner, 1979, for similar results), in particular for discrete stimuli (193 vs.
423 173 ms for DD and TD respectively, Table 1).

In order to examine whether symmetrical patterns were associated with short latencies (saccades aim to target the centre of the word but undershoot their goal) and asymmetrical patterns with long latencies (the eyes land at the location that enables maximum information intake), we calculated (1) an asymmetry index (the difference between the mean amplitude of a child initial saccades in the left and right VFs) and (2) a rapidity index (his or her mean saccade latency, for leftward and rightward saccades) for each participant and each type of target. The correlation between these two indices was not significant with a lack of correlation for words [$r(39) = .05$, $p > .10$], strings of hashes [$r(39) = -.03$, $p > .10$] and solid lines [$r(39) = .07$, $p > .10$]. The same tendency was found when separate analyses were made for TD and DD children [$r(18) = -.19$, $p > .10$, and $r(19) = .40$, $p > .05$, respectively].

3.1.3. Refixation probability

We found a significant effect of group on refixation probability, [$F(1,38) = 6.626$, $p = .014$, $\eta_p^2 = .148$], with surprisingly DD children making less refixations (57.64%) than TD children (68.09%). There was also an interaction between presentation side and group [$F(1,38) = 9.442$, $p = .004$, $\eta_p^2 = .199$], with an "adverse" effect of fixating the RVF among the DD children (as compared to the TD group). Interestingly, the analyses revealed three-way interaction between the group, the presentation side and the type of stimulus [$F(2,76) = 3.632$, $p = .031$, $\eta_p^2 = .087$]. Separate analyses were done for TD and DD children and revealed that the interaction between presentation side and stimulus type was only significant in TD children [$F(2,38) = 3.333$, $p = .046$, $\eta_p^2 = .149$ and $F < 1$, for TD and DD children respectively]. For the DD group analysis, we only found a main effect of the side of presentation [$F(1,19) = 9.005$, $p < .007$, $\eta_p^2 = .322$], with children making more refixations on the RVF (64%) than on the LVF (51%). For the TD group, pairwise comparisons revealed a significant difference between RVF and LVF for words only [$F(1,38) = 8.725$, $p < .01$ for words, and $Fs < 1$ for strings of hashes and solid lines], thus suggesting an advantage for the

RVF limited to word recognition. Note that, even if no reading was required, the bisection task elicited comparable ILPs patterns and a RVF advantage for words in TD children, thus supports the idea that some of the factors responsible for the VF and ILPs asymmetries in natural reading are also at work in this task.

To sum up, saccades toward stimuli located in the RVF were not significantly affected by stimulus type or reading disorder, all children being able to land at the PVL. In contrast, leftward saccades were influenced by stimulus type and reading ability. In particular, the left-right asymmetry of the incoming saccade was influenced by the inter-character spacing in TD children whereas the asymmetry was restricted to words in dyslexics. Moreover, the TD readers fixated closer to the PVL of the discrete stimuli in the LVF compared to the dyslexic children, with leftward saccades about one character longer. These results are consistent with those of Ducrot & Pynte (2002) who showed that expert readers land to the left of the centre in all discrete stimuli (strings of hashes and words) for both presentation sides (see Bellocchi, Mancini, et al., 2013, for similar results in 5^{th} graders). These results suggest that, as a result of reading experience, the children tested in this experiment had already developed automatized routines for programming right-going saccades. The fact that saccades from right-to-left are in the opposite direction of reading would lead to less automatized routines for saccade computation, making them more vulnerable to the influence of reading level and VF. It must be emphasized that many children with dyslexia do not read as much as individuals with typical reading skills, and so, this non-optimal saccade targeting strategy in dyslexia may also results from poor reading experience (see Huettig et al., 2018, for a discussion).

3.2. Comparisons of NF1 children with and without RD

[Insert Table 2 about here]

3.2.1. Saccade size

In clinical populations, as suggested by Ablinger et al. (2014), a "standard way to report on the spatial aspect of eye movement control is to plot the individual distributions of the landing positions of incoming saccades over all letter positions within a target word" (p. 652; see also Radach & Kempe, 1993; Radach & McConkie, 1998).

Zooming in on the frequency distributions of ILPs (Figure 2) reveals different distribution profiles between NF1 children who presented reading disorders (NF1RD) and those without reading disorders (NF1noRD). We found a significant correlation between the reading age of the NF1 children and the frequency of their initial landing position at P2 [$r(18) = .47$, $p < .05$]. Whereas a PVL was distinctly observed in NF1noRD children between the beginning and the centre of the word (i.e., P2), no PVL emerged in NF1RD children [$t(39) = -3.241$, $p < .01$].

[Insert Figure 2 about here]

More precisely, for both groups, there was an interaction between stimulus type and presentation side [$F(2,20) = 7.236$, $p = .004$, $\eta_p^2 = 0.420$ and $F(2,16) = 3.593$, $p = .05$, $\eta_p^2 = 0.313$, for NF1RD and NF1noRD respectively]. For the NF1RD group, pairwise comparisons were used to reveal a difference in initial-saccade size between linguistic stimuli (words) and non-linguistic stimuli (strings hashes and solid lines) [$F(1,20) = 14.323$, $p < .005$]. The difference between strings of hashes and solid lines was non-significant [$F < 1$]. For the NF1noRD group, the amplitude of the initial saccade was similar for words and strings of hashes, but different for solid lines, thus confirming the importance of the discreteness of the stimuli for unimpaired readers [[$F(1,16) = 4.49$, $p = .05$], and [$F < 1$], for (words and strings of hashes) vs. solid lines, and strings of hashes vs. words, respectively].

Of particular interest is that NF1RD readers mirrored the dyslexic eye movement behaviour, with more variability in saccadic programming, and no sensibility to the discreteness of the stimuli (see Figure 3). The data showed no main effect of group [$F < 1$] nor double interaction between presentation side, stimulus-type and group [$F < 1$], but a presentation side × stimulus-type interaction [$F(2,58) = 13.732$, $p < .001$, $\eta_p^2 = .321$], mainly explained by the sensitivity to the linguistic nature of the stimuli [$F(2,58) = 58.81$, $p < .001$, for the opposition between linguistic vs. non-linguistic stimuli, and $F < 1$, for the difference between strings of hashes vs. solid lines].

[Insert Figure 3 about here]

The children with NF1noRD showed fully developed oculomotor mechanisms for efficient reading similar to those of TD children [$F < 1$], with a clear PVL located to the left of the word's centre in both visual fields for the 2 groups [$F < 1$, for the group × presentation side × stimulus type interaction], and fine-tuned saccade targeting guided by the between-character space information. The stimulus-type by presentation-side interaction [$F(2, 54) = 8.088$, $p < .001$, $\eta_p^2 = 0.231$] was explained by the strong difference between ILPs distributions in discrete stimuli (words and strings of hashes) vs. continuous stimuli (solid lines) [$F(1,54) = 10.08$, $p < .01$], the difference between words and strings of hashes being non-significant [$F<1$].

3.2.2. Latency

As detailed in Table 2, for both groups of NF1, there was a main effect of stimulus type [$F(2,20) = 19.360$, $p < .001$, $\eta_p^2 = .638$ and $F(2, 16) = 50.890$, $p < .001$, $\eta_p^2 = .864$, for NF1RD and NF1noRD respectively]. This difference was mainly explained by shorter

latencies for discrete stimuli than for continuous stimuli [$F(1,20) = 38.620$, $p < .001$ and $F(1,16) = 101.705$, $p < .001$, for NF1RD and NF1noRD respectively].

Consistent with what had previously been observed for saccade size, the saccade latencies of NF1RD children were similar to those of DD children. There was a main effect of stimulus type [$F(2,62) = 40.205$, $p < .001$, $\eta_p^2 = .565$] regardless of the group [$F < 1$]. Similarly, the saccade latencies in NF1noRD were similar to those found in TD children, with shorter latencies when targeting discrete stimuli and longer saccade latencies for continuous stimuli [$F(2,54) = 119.607$, $p < .001$, $\eta_p^2 = .816$]. There was no main effect of group [$F < 1$] nor interaction between stimulus-type and group [$F < 1$]. These results seem to suggest that it is less time-consuming to target the PVL in a word (or in a linguistic-like stimulus) than to target the middle of a solid line.

3.2.3. Refixation probability

We found a significant interaction between stimulus type and presentation side, for both groups of NF1 [$F(2,20) = 3.569$, $p = .047$, $\eta_p^2 = 0.263$ and $F(2,16) = 3.639$, $p = .050$, $\eta_p^2 = .313$ for NF1RD and NF1noRD respectively]. In line with what had previously been observed for TD children, pairwise comparisons in the NF1noRD group revealed a significant effect of the VF for words on the refixation probability [$F(1,16) = 10.156$, $p < .005$ for words, and no VF difference for strings of hashes and solid lines, $Fs < 1$]. For the NF1RD group, pairwise comparisons yielded an opposite effect, with children performing more refixation on words in the RVF [$F(1,20) = 9.028$, $p < .01$ for words and $Fs < 1$ for strings of hashes and solid lines].

When pooling the data of NF1noRD and TD children, this interaction remained [$F(2,54) = 4.666$, $p = .014$, $\eta_p^2 = 0.153$], and could be entirely explained by a larger VF asymmetry for words [$F(1,54) = 20.643$, $p < .001$ for words, and $Fs < 1$ for strings of hashes and solid lines]. Note that this larger VF asymmetry for words also resulted in a larger “linguistic” effect in

RVF than in LVF. Comparing NF1RD performance with that of DD children, the ANOVA showed no main effect of participant group [$F < 1$] nor double interaction between presentation side, stimulus-type and group [$F < 1$]. We found, however, a main effect of presentation side [$F(1,29) = 7.448$, $p = .011$, $\eta_p^2 = .204$] and a presentation side × stimulus-type interaction [$F(2,58) = 4.055$, $p = .022$, $\eta_p^2 = 0.123$], mainly explained by the cost for word recognition in the RVF [$F(1,58) = 37.383$, $p < .001$ for words, and $Fs < 1$ for the strings of hashes and solid lines]. Here again, the difference between words and non-linguistic stimuli was larger in the RVF than in the LVF (but in reverse). The opposite effects in the VF asymmetries found for children with and without RD suggests that the parafoveal words were processed (even if no linguistic processing was required in the bisection task), resulting in a classical RVF advantage for children without RD and a cost for the children with RD.

To sum up, the eye movements of NF1RD children during the ocular bisection task are different from those of NF1noRD children, but similar to those of DD children. In particular, our results showed a less pronounced left-right asymmetry in the saccade amplitude for RD children than for TD and NF1noRD children. This pattern of result reflects, in the context of reading deficits, less stable ILPs and a not yet automatized saccade targeting strategy. This is consistent with the data obtained on the VP effect in foveal vision, showing reduced left-right asymmetry in the RD children's VP-curve (Bellocchi & Ducrot, 2021; Ducrot et al., 2003). The fact that NF1RD and children with dyslexia showed similar saccade targeting strategy, is consistent with the proposition of Huettig et al. (2018) that "this at least partly reflects their common reduced reading experience rather than a causal impairment due to a reading disorder" (p. 339).

3.3. Cross-population results

Each child was assigned an ILP index (their initial-landing position for words in the RVF) and a reading level index (their reading age[3]). The correlations between these two measures are displayed in Figure 4. We found a significant correlation between reading age and the initial landing position at P2 [$r(59) = .493$, $p < .001$], with a higher reading level being associated with a higher probability to land first at the PVL (i.e., P2). A significant negative correlation was also found between reading age and the initial landing position at P1 [$r(59) = -.266$, $p < .05$], suggesting that poor readers are more likely to land at the beginning of the word. Note that no significant correlation was shown for landing positions at P3 [$r(59) = -.136$, $p > .05$].

[Insert Figure 4. about here]

Cluster analyses with a three-group solution yielded a relatively distinct separation of participants into clusters with very little overlap. Figure 5 shows the three clusters of participants for the distribution of the ILP frequency at each position and the relationship between reading level and ILP. This allowed for an evaluation of the ways in which our readers are similar or different in reading skills and eye movement behaviour. This analysis strategy is supported by the idea that, as word identification becomes more efficient, children shift from a letter-by-letter sequential decoding strategy (characterised by ILPs close to the word beginning to be able to scan it from left to right) to more parallel processing (with ILPs shifted toward the word centre (see also, Ablinger et al., 2013; Schattka et al., 2010). Cluster 2 comprised almost half of the participants (46%, mainly children without RD) and corresponds to an expert reader strategy with an ILP most of the time at the PVL (i.e., P2).

[3] We chose to use the reading age measure since it is frequently used in eye-tracking and dyslexia studies (e.g., Bellocchi et al., 2019; Liu et al., 2022; Prado et al., 2007). Note that this measure was strongly correlated in the present study with the other two reading indices of the Alouette-test [reading accuracy, $r(59) = .684$, $p < .001$; reading fluency $r(59) = .911$, $p < .001$].

589 The two remaining clusters differed from the cluster of "typical" readers. Cluster 1 (12%,
590 mainly DD) showed a more careful eye-movement strategy (i.e., fixated closer to the
591 beginning of the stimuli, P1), as usually found for beginning readers. It comprised readers
592 with the lowest reading level scores, and this group might stick to serial reading, suggesting
593 an immaturity of the oculomotor control associated with a sequential processing strategy.
594 Members of Cluster 3 (42% of the participants, mainly RD children) presented an
595 intermediate reading level and a flattened curve with an ILP covering a wider area around the
596 centre of the word. This pattern could be the reflect of an oculomotor instability. In that sense,
597 this subgroup of readers also presented severe visual-processing deficits at the DEM-test (-
598 1.27 SD on the VT index and -1.97 SD on the HTaj index, with 41% of the children below -
599 1.5 SD on the VT index, and 59% below -1.5 SD on the HTaj index)[4].

600 We want to draw attention to the fact that the 3 clusters differed[5] significantly in terms
601 of reading level [$F(2,58) = 3.877$, $p < .05$, $\eta_p^2 = .118$]. The pairwise comparisons showed a
602 significant higher reading age in the cluster 2 (Mean = 115.61) compared with the cluster 1
603 (Mean = 94.43; $p < .05$) and 3 (Mean = 100.81; $p < .05$), respectively. However, no significant
604 difference emerged between clusters 1 and 3 in terms of reading age [$p > .05$] and between the
605 3 clusters in terms of chronological age [$F(2,58) = 0.647$, $p > .05$, $\eta_p^2 = .022$].

606 To sum up, taken together, the correlation and cluster analyses revealed a strong link
607 between reading expertise and ILP. Cluster analyses also pointed to individual differences,
608 with three subgroups of readers using different saccade targeting strategies, irrespective of
609 whether they have been classified as neurotypical, dyslexic or NF1. In our view, the present

[4] Note that the cluster 1 group had significantly poor performance at the DEM-test, as well, probably linked to their slowness in their responses and their low reading age (-2.19 SD on the VT index and -1.65 SD on the HTaj index). No such visual-processing deficits was observed in cluster 2 ($-1 < SD < 0$, for the VT and HTaj index).

[5] For these statistical analyses, Kruskal–Wallis tests followed by Dunn–Bonferroni method for pairwise comparisons were carried out.

results strongly suggest that the reading ability and the mode of processing used (shift from a sequential reading to a more parallel orthographic processing) are sufficient to account for the different patterns of eye movement behaviour.

[Insert Figure 5 about here]

4. DISCUSSION

The aim of the present study was to investigate the extent to which attentional factors, stimulus features, and reading ability influence the position where the eyes first land in a target (word or non-linguistic stimulus) displayed in parafoveal vision. A secondary objective was to better understand the relationship between saccade eye movements and reading difficulties and to examine the possible modulation of clinical diagnosis (DD and NF1) and reading skills (good and poor readers) on saccade targeting strategies as expressed by ILPs.

4.1. What determines where children first fixate?

As previously demonstrated by Ducrot et al. (2013), our data showed that all children tend to initially fixate words at a point somewhere between the beginning and the centre of the word while executing rightward saccades, regardless of their reading level (with or without RD) or clinical diagnosis (dyslexics or NF1 group). In other words, even with a minimum experience with reading, children show an adult-like PVL pattern in the RVF (for similar results, see Bellocchi et al., 2019; Ducrot et al., 2013; Joseph et al., 2009). Note that rightward saccades represent the most frequent saccades in left-to-right writing systems, leading to early development of automatized procedures for saccade computation.

One aspect that warrants particular attention is the left-right asymmetry in the saccade size launched toward parafoveally located stimuli. As stated before, "linguistic-like" stimuli encourage a saccade targeting strategy that aims to land at the PVL in both VFs, with greater difficulty in reaching this goal for the LVF due to the greater distance and unusual reading direction (Ducrot & Pynte, 2002; Vitu et al., 1995). Our results showed a more pronounced left-right asymmetry for TD and NF1noRD children than for DD and NF1RD readers (see Bellocchi et al., 2019, for similar results with DD). One possible explanation to account for this increase in asymmetry for TD readers was suggested by Huang et al. (2019), as reading experience seems to "increase the ratio between recognition in the centre and recognition away from the centre of fixation, as reflected in the changes of the shape of the so-called Form Resolving Field (which maps the distribution of recognition accuracy onto eccentricity) from symmetrical and reversed-V-shaped to slightly narrower on the side of the reading direction" (see also, Lorusso et al., 2004; Zegarra-Moran & Geiger, 1993). Moreover, children without RD used a saccade targeting strategy that aims to land left of centre (PVL) for all discrete stimuli (i.e., with inter-character spaces), even in the LVF, as already observed in adults (Ducrot & Pynte, 2002). In contrast, for children with RD, the asymmetry was less pronounced and restricted to words only. NF1RD and DD children were influenced by the linguistic nature of stimuli, such that they do tend to initially fixate words closer to their beginning (as compared to the strings of hashes).

The results, therefore, suggest that the pre-processing mechanism responsible for the direction of attentional scanning (left-to-right) proposed in Ducrot and Pynte (2002) is well automatized in children without RD, which "anticipated doing left-to-right attentional scanning of discrete stimuli and took the direction of this upcoming attentional scanning into account when computing the incoming saccade" (Ducrot & Pynte, 2002, p. 1142). Note that the fact that children used different saccade targeting strategies depending on the presence of

inter-character spaces or the linguistic nature of the stimulus suggests that the left–right asymmetry in the PVL effect may not result *only* from oculomotor constraints associated with saccade execution.

4.2. How reading ability affects eye movement behaviour?

A major aim of the present study was to determine whether reading level and changes in written language experience over the course of DD, NF1 and TD children's developmental trajectory are associated with changes in reading strategies, as indexed by saccade targeting strategies. Firstly, the individual distributions of first fixation positions were modulated by reading skills. Cluster analyses confirmed that the landing position of eye movement saccades on words is a sensitive index of reading efficiency (Ducrot et al., 2013; Joseph et al., 2009; Juhasz et al., 2008), with three subgroups of readers using different saccade targeting strategies, irrespective of whether they have been classified as neurotypical, dyslexic or NF1. Good readers (cluster 2) made their first fixation most of the time at the PVL whereas, in children with poor reading skills, ILPs either occurred at the beginning of the word (cluster 1) or covered a wider area around the centre of the word with high variability (cluster 3). A convincing explanation for these saccade targeting differences is based on the dual-route model of reading (Coltheart et al., 2001). As experience with written language grows, children shift from a letter-by-letter sublexical decoding strategy to more parallel lexical processing (Frith, 1985). In that sense, Tydgat and Grainger (2009) suggested that as children develop their capacity to perform parallel letter processing, their ILPs shift from being close to the beginning of words toward a position closer to the centre of words (see also Huestegge et al., 2009). Meanwhile, visuo-attentional abilities would gradually develop with reading experience (Bosse & Valdois, 2009; Hawelka & Wimmer, 2005). In that vein, children show a smaller span of effective vision than adults (Häikiö et al., 2009; Rayner, 1986), the size of

children's perceptual span increasing with reading proficiency (Sperlich et al., 2016). It may be that in very fluent reading, the visuo-attentional capacity approaches visual acuity constraints for letter encoding (Hautala et al., 2022).

We also explored the impact of the reading level on the VF effects. Children with RD made shorter saccades in words than did TD readers, with ILPs located left of centre for both left and right VF only for the TD children. One possibility is that children with RD experience difficulties in oculomotor control. Shifted ILPs may arise simply because children with RD, as beginning readers, exhibit shorter average saccade amplitude (cluster 1) and/or increased variability (cluster 3) in these saccade amplitudes (see also Ducrot et al., 2013, for a similar finding with a lateralized lexical decision task). In line with this proposal is the fact that an eye-tracking training can improve saccadic eye movements in beginning children, with accurately aiming for the OVP of each word (Lehtimäki & Reilly, 2005). It is also possible that oculomotor behaviour and saccade targeting strategy depend on the efficiency of linguistic processing (Rayner, 1998). Proficient readers with high-quality lexical representations and efficient lexical processing will aim to optimize information uptake from words by initially fixating the OVP. In contrast, beginning or poor readers, relying on a letter-by-letter phonological decoding strategy, will prefer to initially fixate words closer to their beginning. In that sense, shorter incoming saccade amplitudes and increased refixation rates have been reported in poor, dyslexic, beginning, and slow readers (e.g., Ducrot et al., 2013; Hawelka et al., 2010; Huestegge et al., 2009; McKeben et al., 2004; Rayner et al., 2010, but see also Valdois et al., 2004, for the hypothesis that dyslexic readers suffer from a narrowed visual attentional window). However, if the second account was the sole explanation, then why would DD and NF1RD children aim to land to the right of the middle of a word displayed in the LVF? Because acuity drops rapidly with increasing eccentricity, word recognition is assumed to be better when the initial fixation is left rather than right of the

centre of the word. Rather, these results suggest that oculomotor behaviour change as linguistic processing becomes more efficient, thus confirming that poor and proficient readers face different oculomotor, perceptual, and cognitive constraints when reading.

As a whole, the current results support the hypothesis that saccade targeting strategies are an acquired reading skill that develops with reading experience. Conversely, the children's reading strategies (i.e., whether they use lexical or sublexical route) can be understood from the characteristics of saccadic eye movement.

4.3. A Causal Role for Inefficient Eye Movements in Reading Disability?

Everyone agrees that DD readers' eye movements are different from typical readers. These eye movement differences have been found when reading isolated words/pseudowords, sentences or texts, and were reported in different languages with different orthographic depths (e.g., Hutzler & Wimmer, 2004; Hutzler et al., 2006). It has been suggested that they might result from poor oculomotor control associated with dyslexia (Pavlidis, 1981). However, evidence in support of a low-level oculomotor account of the reading behaviour of dyslexics are highly controversial (e.g., Eden et al., 1994; Stanley et al., 1983; Stein et al., 1988, for reviews, see Rayner, 1998).

Understanding the source of such differences in eye movements has been the focus of this work, a sample of children with dyslexia while also examining another neurodevelopmental disorder, known to present high comorbidity with RD. In line with previous observations, we found different saccadic programming in children with RD. DD children and NF1 with RD presented longer latencies than TD children, in particular for discrete stimuli (see also Bucci et al., 2008). Differences in the left-right asymmetry in the saccade size were also shown between groups, as previously discussed above. RD readers

were able to accurately perceive and use parafoveal visual information in order to guide their eyes during text reading, at least in the usual reading direction. However, they revealed a greater difficulty in reaching the centre of targets presented in the LVF due to the greater distance and an unusual reading direction. McKeben et al. (2004) have previously shown that "a mechanism for adapting the gain of reactive, stimulus-triggered saccades (Deubel, 1995) was active during reading in dyslexics, but that it was quantitatively less developed" (p. 396). Moreover, RD children didn't show the classical asymmetrical landing position pattern for "linguistic-like" stimuli (with inter-character spaces). This suggests that in poor readers, the preprocessing mechanism that detects the presence or absence of spaces between characters and responsible for the direction of attentional scanning is not entirely operational, in particular for the LVF. This result could be interpreted as a deficient allocation of visual attention in RD children hampering the exact planning of fine-tuned leftward saccades (e.g., Facoetti, 2012; Facoetti et al., 2010; Lobier et al., 2012; Valdois et al., 2004; see Gavril et al., 2021 for a meta-analysis). In that sense, it was reported that the orienting visuospatial attention is impaired in dyslexia with a LVF "mini-neglect" and a RVF over-distractibility (Facoetti, 2001; Hari, 2001; Hari & Renvall, 2001). The similar pattern of results for RD and beginning readers (i.e., ILPs determined by the linguistic nature of stimuli instead of the presence of inter-character spaces; Bellocchi, et al., 2013) speaks against this view. We rather suggest that the lack of sensibility to the discreteness of the stimuli we observed in RD children in the saccade computation, reflects their reading difficulties and/or a lack of experience with written language (see also Hawelka et al., 2006). The cluster analyses support this idea with children of cluster 1 (with the lowest reading level scores) showing an immature saccade targeting strategy (characterised by ILPs near the words' beginning and sequential reading), which mirrors their poor reading skills. That goes in line with the above findings on the asymmetry of the saccade extent and the data of Franzen et al. (2021) showing "a

laborious and more effortful reading strategy in DD, resembling a pattern observed in beginning and poorer readers" (Franzen et al., 2021, p. 9, see also Ashby et al., 2005; Rayner, 1998). These findings can be accounted for by assuming that visual attention distribution (as expressed by ILP) adapts to the differences in reading experience. Therefore, an important result to retain from our study is that eye movements per se are not a cause of dyslexia.

What about the children of cluster 3? They presented an intermediate reading level and exhibits an increased variance in the saccade amplitudes resulting in a flattened and diffuse LP-curve. According to Snell and Theeuwes (2020), a clean oculomotor behaviour is reflected in a narrower spread of ILPs, around the PVL (as observed in experienced readers of the cluster 2). ILP spreads in cluster 3 readers widened upon an increased number of positions. Note that the cluster 3 comprised 70% of reading-disabled children (mainly DD). Interestingly, it has been reported that individuals with DD demonstrate a more distributed/diffused mode of attention and have difficulty in narrowing their focus of attention (Facoetti et al., 2000, 2003; Franceschini et al., 2012). Such detrimental effect of the increased variability in the ILPs received support from two recent studies (Franzen et al., 2021; Rima & Schmid, 2021). Franzen et al. (2021) found an increased number of unexpected/atypical saccades in readers with dyslexia, thus suggesting that their eyes occasionally move to seemingly random places. Regarding the distribution of the children's ILPs in the cluster 3, it is conceivable that an increased oculomotor instability would result in more spatial variability in ILPs. Taken together with the performance at the DEM-test, this pattern of results may reveal possible occasional oculomotor control deficits in RD, as already reported in previous studies (e.g., Freedman et al., 2017; Raghuram et al., 2018; Tiadi et al., 2016; Vagge et al., 2015), which might arise from underlying visual-processing deficits, such as visuo-attentional deficits (Facoetti et al., 2003, 2019; Franceschini et al., 2012, 2022; Valdois et al., 2004; Vernet et al., 2022).

The point of particular interest is that poor NF1 readers mirrored the dyslexic eye movement behaviour, with less accuracy and more variability in saccadic programming, no sensibility to the discreteness of the stimuli, particularly in the LVF. Proficient NF1 readers showed fully automatized oculomotor mechanisms for proficient reading, as TD children do, using a saccade targeting strategy that aims to land left of the centre for all discrete stimuli so as to be able to scan the stimulus from left to right, thus left-shifting PLP for both left and right VF. Note that it was the first study investigating eye movement control related to reading context in NF1. We provided key evidence showing a difference in the saccadic targeting strategies used by NF1 children depending on the presence of a RD associated. In addition, the atypical saccade targeting strategies used by NF1RD children (timid eye-movement strategy in cluster 1 and inaccurate ILPs in cluster 3) were not specific to this disease. Finally, the fact that NF1RD and DD children showed similar saccade targeting strategies gives clear empirical support to the idea that this at least partly reflects their common poor reading skills (probably related to their limited reading experience, see Cunningham & Stanovich, 1997; Goswami, 2015) rather than an impairment causally related to a reading disorder.

There are some limitations to the present study. The first limitation regards the generalizability of the findings with the small sample size of the two NF1 groups due to the prevalence of this rare disease and our strict inclusion and exclusion criteria. For instance, we have made the choice not to include NF1 children with comorbid ADHD although the large proportion of ADHD in this population (i.e., 40%, Hyman et al., 2005). But our priority was to ensure that our results accurately reflect saccade targeting strategies associated with a RD without possible modulation related to inattentive or impulsive behaviour. Another limitation comes from the absence of a direct measure of print exposure to measure the amount of children's reading and be able to identify the impoverished reading experience

of RD children as a causal claim. One way could be to systematically include in our future studies traditional self-report questionnaires and print exposure checklists assessing parents' familiarity with children's book titles (see Mol & Bus, 2011, for a meta-analysis). In addition, the heated debate on the causes of dyslexia needs more longitudinal studies starting in kindergarteners to increase the likelihood of being able to reliably identify explicit causal links.

What should be taken from the individual analysis is that most of the DD readers of our sample do not exhibit oculomotor deficits (see Hutzler et al., 2006; Prado et al., 2007, for similar conclusions with non-linguistic tasks). Furthermore, many of the impairments displayed by RD children are also shown by beginning readers or illiterate individuals who have received very little reading instruction, thus suggesting that eye movements are functional and perform the same function in DD readers that they do in proficient readers. We suggest that such differences in performance between children with and without DD are, to a substantial extent, the consequence of their poor experience with written language. Specifically, disruption to oculomotor behaviour simply reflects the fact that many of the component processes involved in learning to read have not yet become fully automatized (LaBerge & Samuels, 1974). For DD readers who exhibited deviant saccade targeting strategies, the possibility of occasional oculomotor control deficits cannot be entirely ruled out supporting the notion that non-linguistic processes could serve as an additional source to explain their impaired reading. Although these low-level oculomotor deficits in dyslexia are difficult to quantify, it would be important to propose a careful assessment of the visual-processing and visuo-attentional skills underlying reading to ensure diagnostic and targeted intervention adapted to their deficiencies.

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DECLARATION OF COMPETING INTEREST

The authors have no conflicts of interest to disclose.

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1281 Table 1. Mean of initial saccade size (in characters), saccade latency (in milliseconds) and
1282 refixation probability (in percent) as a function of stimulus type, visual field and group in
1283 Experiment 1.

	Initial saccade size Mean (SD)		Saccade latency Mean (SD)		Refixation probability Mean (SD)	
	TD	DD	TD	DD	TD	DD
Left Visual Field						
Words	4.33 (0.74)	3.95 (1.30)	170.55 (13.86)	194.94 (28.02)	74.32 (19.69)	55.75 (24.52)
Strings of hashes	4.34 (0.93)	3.72 (0.64)	173.59 (19.96)	193.64 (25.79)	69.24 (24.72)	49.20 (22.42)
Solid lines	3.59 (0.84)	3.64 (0.99)	217.92 (28.47)	220.19 (29.70)	69.02 (19.53)	48.93 (21.98)
Right Visual Field						
Words	3.40 (0.78)	3.27 (0.87)	173.85 (21.51)	191.36 (33.15)	53.64 (28.45)	72.34 (24.84)
Strings of hashes	3.49 (0.54)	3.63 (0.56)	173.91 (21.84)	192.18 (38.67)	70.88 (22.71)	59.44 (22.77)
Solid lines	3.54 (0.59)	3.60 (0.57)	221.18 (17.23)	220.63 (24.91)	71.43 (24.44)	60.17 (26.62)

1284 *Notes.* Saccade size was measured according to the central fixation point. TD: typically
1285 developing children; DD: children with developmental dyslexia.

1286

Table 2. Mean of initial saccade size (in characters), saccade latency (in milliseconds) and refixation probability (in percent) as a function of stimulus type, visual field, and group in Experiment 2.

	Initial saccade size Mean (SD)		Saccade latency Mean (SD)		Refixation probability Mean (SD)	
	NF1noRD	NF1RD	NF1noRD	NF1RD	NF1noRD	NF1RD
Left Visual Field						
Words	4.46 (0.71)	4.22 (0.52)	173.91 (8.81)	188.88 (12.88)	74.96 (25.10)	47.79 (26.49)
Strings of hashes	4.43 (0.26)	3.55 (0.55)	175.38 (11.29)	191.10 (19.02)	71.03 (23.59)	51.89 (23.82)
Solid lines	3.67 (0.96)	3.64 (1.22)	219.34 (32.24)	222.05 (35.39)	69.05 (24.85)	45.98 (23.06)
Right Visual Field						
Words	3.43 (0.57)	3.34 (0.63)	173.47 (15.93)	182.89 (12.20)	53.92 (33.42)	72.41 (21.02)
Strings of hashes	3.50 (0.90)	3.53 (0.70)	174.61 (14.54)	184.78 (17.63)	70.24 (25.97)	47.05 (29.55)
Solid lines	3.67 (1.18)	3.52 (0.65)	220.33 (22.14)	222.51 (25.85)	71.11 (30.09)	47.65 (23.47)

Notes. Initial saccade size was measured according to the central fixation point. NF1RD: NF1 children with reading disorders; NF1noRD: NF1 children without reading disorders**.**

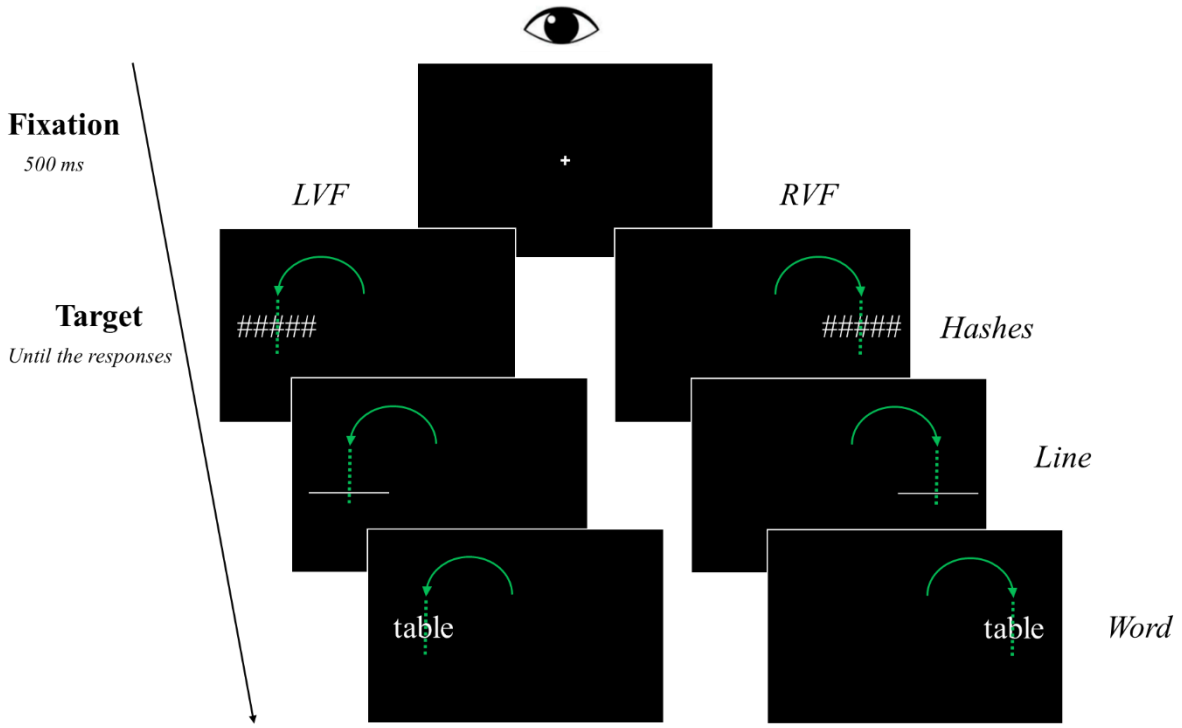

Figure 1. Procedure used in the oculomotor lateralized bisection task. The different display conditions of the stimuli are represented in this figure with the 3 types of stimuli (words, hashes and lines) and the 2 visual fields of presentation (LVF and RVF). When the target item appeared, participants were instructed to move their eyes to look at what they considered to be the middle of the item (see arrows and dashed vertical lines in the figure).

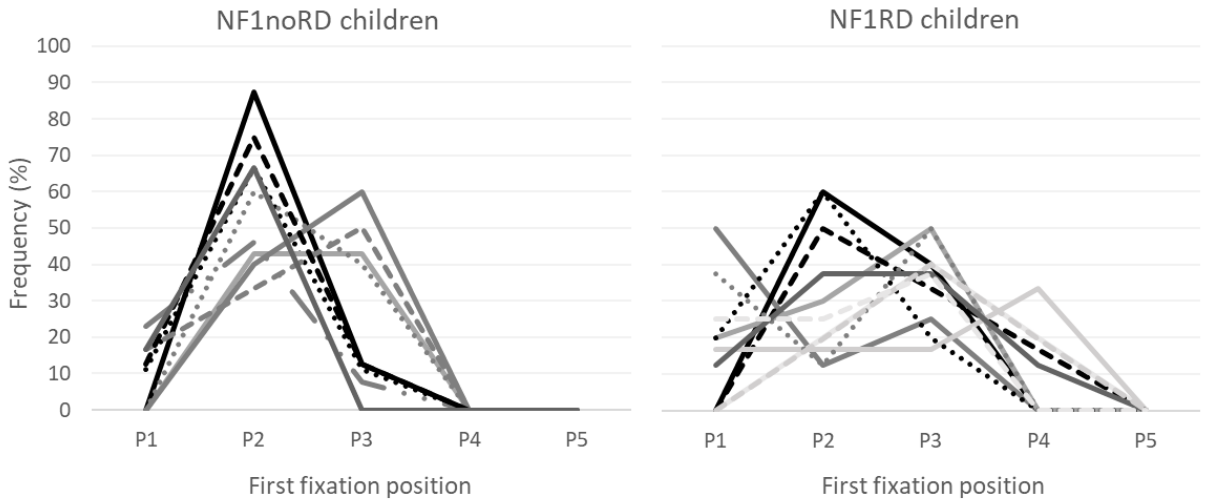

Figure 2. Individual distribution of first fixation position specifically for words presented in the RVF in NF1noRD (i.e., left part of the figure) and NF1RD (i.e., right part of the figure) children.

Notes. This representation was made only for the words presented in the RVF to observe the oculomotor behaviour in the most reading-like situation. Each line represents the individual performance of a different participant. NF1RD: NF1 children with reading disorders; NF1noRD: NF1 children without reading disorders.

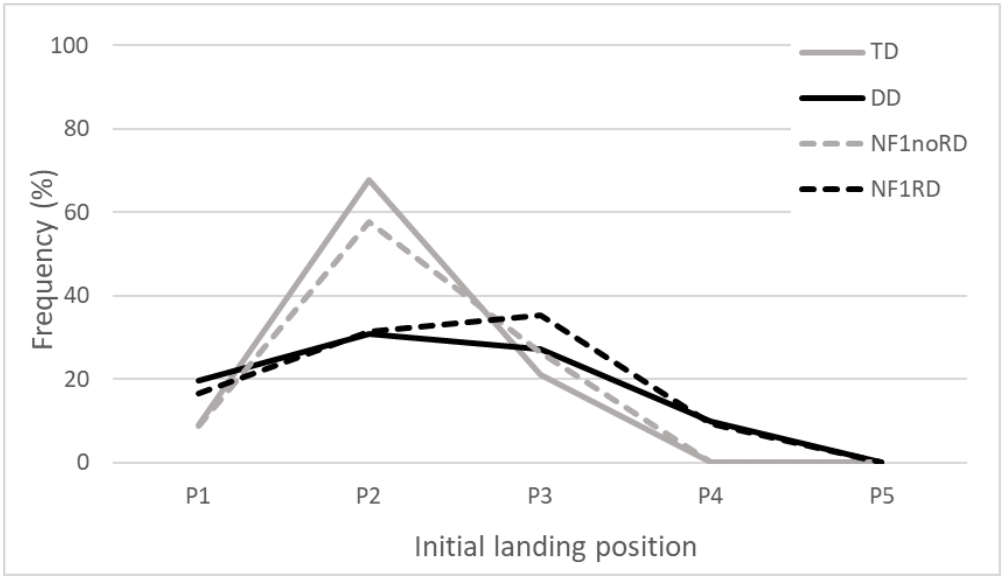

Figure 3. Comparison of the initial landing position's frequency for words in the RVF between the 4 groups of children in Experiment 1 and 2.

Notes. This representation was made only for the words presented in the RVF to observe the oculomotor behaviour in the most reading-like situation. TD: Typically developing children; DD: children with developmental dyslexia; NF1RD: NF1 children with reading disorders; NF1noRD: NF1 children without reading disorders.

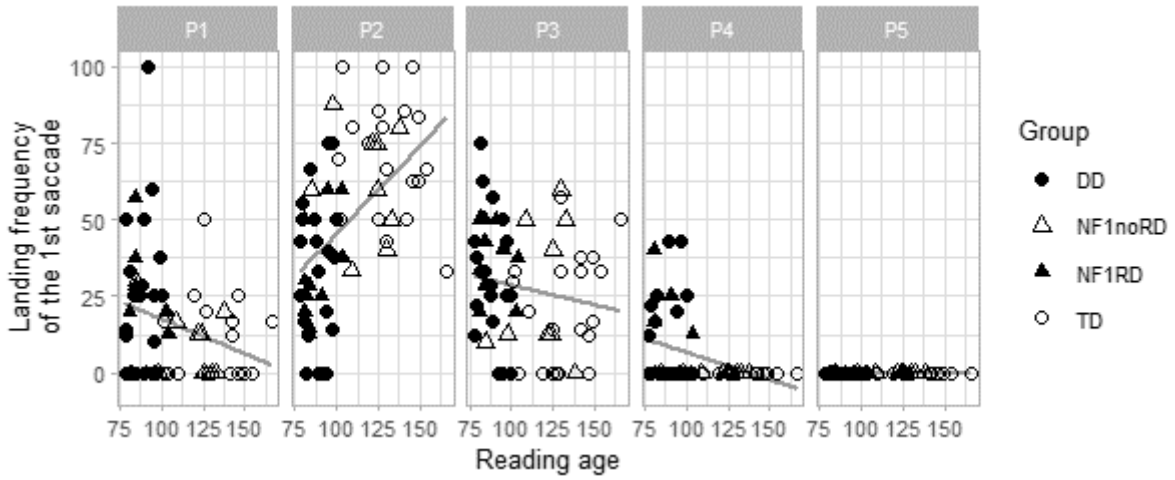

Figure 4. Frequency of the initial landing of the first saccade (in percentage) at each position of words according to reading age (in months) and groups.

Notes. These representations were made only for the words presented in the RVF to observe the oculomotor behaviour in the most reading-like situation. TD: Typically developing children; DD: children with developmental dyslexia; NF1RD: NF1 children with reading disorders; NF1noRD: NF1 children without reading disorders.

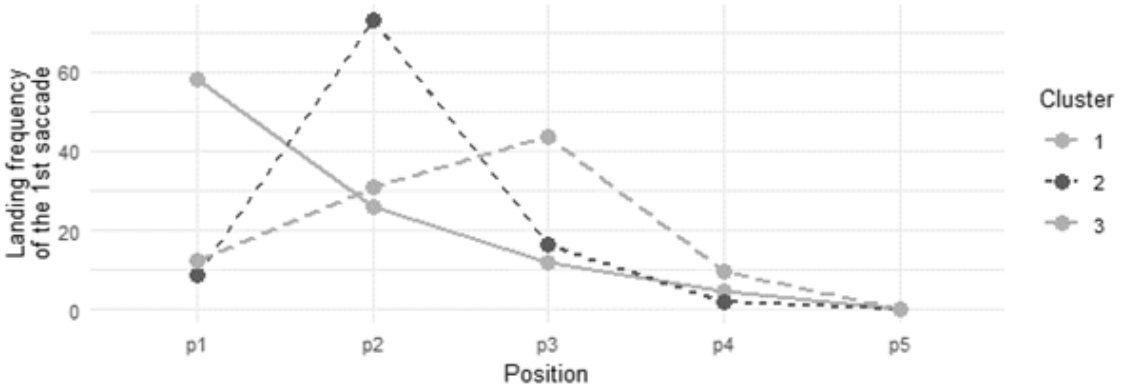

Figure 5. Distributions of the initial landing position (in percentage) according to the 3 clusters found for all groups combined.

Notes. This figure was made only for the words presented in the RVF to observe the oculomotor behaviour in the most reading-like situation.