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The determinants of saccade targeting strategy in neurodevelopmental disorders: the influence of suboptimal reading experience

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ABSTRACT

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

45

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

48 **ABBREVIATIONS.**

| | | |
|----|---------|--|
| 49 | DD | Children with developmental dyslexia |
| 50 | ILP | Initial landing position |
| 51 | LVF | Left visual field |
| 52 | NF1 | Neurofibromatosis type 1 |
| 53 | NF1RD | Children with neurofibromatosis type 1 with reading disorders |
| 54 | NF1noRD | Children with neurofibromatosis type 1 without reading disorders |
| 55 | PVL | Preferred viewing location |
| 56 | RAN | Rapid Automatized Naming |
| 57 | RD | Reading disorders |
| 58 | RVF | Right visual field |
| 59 | TD | Typically developing children |
| 60 | VP | Viewing position |

61 1. INTRODUCTION

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

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

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

86 The present study further investigates the perceptual and attentional factors that
87 determine the eyes' landing position in children and whether or not the pattern of eye
88 movements (and in particular the primary saccade landing sites) can provide useful
89 information to help characterize the reading skills in neurodevelopmental disorders. Word
90 length, that is provided by the visually salient extra spacing between words, in most languages
91 that use an alphabetic script, is a primary source of information in order to guide the eyes
92 during text reading and determine where the eyes first land in a word (e.g., Inhoff et al., 2003;
93 Rayner et al., 1998). Rayner (1979) first demonstrated that the landing position in a word
94 during continuous reading, referred to as the "preferred viewing location" (PVL), is usually
95 located halfway between the beginning and the middle of the word for languages read from
96 left-to-right (McConkie et al., 1988; Radach & Kempe, 1993; Rayner, 1979; Vitu et al.,
97 1990). It is thought that the PVL reflects a strategy whereby readers aim to fixate the centre of
98 the word (e.g., McConkie et al., 1988; Reichle et al., 2003; but see Vitu, 2003) and fall short
99 of that optimal viewing position (OVP) (i.e., saccades would undershoot their goal), owing to
100 the properties of the oculomotor system (Engbert & Krügel, 2010; Joseph et al., 2009;
101 McConkie et al., 1988; Nuthmann et al., 2005; O'Regan & Lévy-Schoen, 1987).
102 Alternatively, a visual strategy could be developed to send the eyes to a location that
103 optimizes information uptake from the fixated word (Legge et al., 1997; O'Regan & Lévy-
104 Schoen, 1987). The evidence strongly suggests that in addition to length information, salient
105 orthographic information can be extracted from the parafovea and influence saccade
106 computation (e.g., orthographically unfamiliar initial trigrams, Hyönä, 1995; White &
107 Liversedge, 2006). Furthermore, developmental research suggests that beginning readers do
108 learn to optimize saccade targeting strategies, with average initial landing positions (ILPs)
109 gradually shifted towards the word centre during the first years of formal reading instruction
110 (Ducrot et al., 2013; Huestegge et al., 2009; Joseph et al., 2009; Vorstius et al., 2014). Based

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

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

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

141 A huge amount of data has reported differences between the eye movement patterns of
142 dyslexic readers and those of skilled readers. Poor readers and individuals diagnosed as
143 having dyslexia exhibit inefficient oculomotor behaviour while reading, with longer saccades,
144 shorter fixations, and more refixations than typical readers (Ashby et al., 2005; Franzen et al.,
145 2021; Gagl et al., 2014; Gangl et al., 2018; Hawelka et al., 2010; Kirkby et al., 2022; Lefton
146 et al., 1979; Prado et al., 2007; for review, see Rayner, 1998). Also relevant for the present
147 study are experiments reporting a missing parafoveal preview benefit in poor readers or
148 dyslexic children (Silva et al., 2016). The difficulty of pre-processing the word to the right of
149 fixation may affect both saccade-planning and its execution towards the PVL. In that sense,
150 dyslexic readers tend to initially fixate words closer to their beginning than good readers
151 (Gagl et al., 2014; Gangl et al., 2018; Hawelka et al., 2010; Kirkby et al., 2022; McDonald et
152 al., 2006; McKeben et al., 2004). However, there is still some unsettled disputes on the role of
153 these atypical eye movement patterns as a causal factor in dyslexia (see Blythe et al., 2018,
154 asserting that instead they might primarily reflect an underlying difficulty in written word
155 recognition or decoding). Indeed, the attempts to replicate differences in eye-movement
156 patterns of dyslexic, poor and control readers when performing nonreading tasks have been
157 essentially unsuccessful, suggesting that children “with delayed reading skills (identified by
158 an assessment of age referenced reading ability rather than a diagnosis of dyslexia possess the

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

161 The point of agreement is that in a reading task, children with DD exhibited atypical
162 visual-processing skills. Among them, the deployment of visual attention seems to be
163 impaired in DD individuals. As mentioned above, several studies have shown that in left-to-
164 right reading systems, the fixation point of skilled readers was often located toward the left of
165 the strings, when they processed multiple characters at once, under the influence of reading
166 habits and experience (e.g., Ducrot & Pynte, 2002; Sireteanu et al., 2005), suggesting a left
167 dominance of attention distribution in the process. DD children have a deficit in RVF
168 attentional inhibition, and their attentional resources can be excessively interfered by RVF
169 information (Li et al., 2021). It results in the ignorance of LVF information (see Facoetti et
170 al., 2006; Hari & Renvall, 2001), which leads to no significant difference between LVF and
171 RVF, showing an unbiased distribution pattern of attention resources (Li et al., 2021). In that
172 vein, Ducrot and colleagues found a symmetric OVP curve for dyslexic readers in foveal
173 vision, contrary to control who demonstrated a typical OVP effect with a left-right
174 asymmetric J-shape curve (Bellocchi & Ducrot, 2021; Ducrot et al., 2003, see also Bellocchi
175 et al., 2019, for a less pronounced left-right asymmetry in parafoveal vision). In addition,
176 children with DD are more affected by visual crowding (even with non-linguistic stimuli, Joo
177 et al., 2018; Spinelli et al., 2002) and benefit more from increased text spacing (Perea et al.,
178 2012; Zorzi et al., 2012; for reviews, see Bellocchi et al., 2013; Gori & Facoetti, 2015).
179 Finally, the atypical eye-movement patterns observed in dyslexic children have been linked to
180 impaired visuo-attentional processing, and poor visual attentional span abilities, resulting in
181 fewer letters simultaneously processed and more rightwards fixations (Prado et al., 2007). As
182 suggested by Facoetti (2012), a possible neurobiological substrate of visuo-spatial attention
183 deficits in DD could be a weakened or abnormal magnocellular input to the dorsal visual

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

188 One of the main motivations of the study was to examine whether deviant eye
189 movements exhibited by dyslexic readers are a symptom of dyslexia or constitute a more
190 causal impairment. Few studies have explored eye movement behaviour in children with a
191 range of reading abilities that goes beyond dyslexia, using eye tracking during a task
192 preserving the perceptual and oculomotor demands of reading (but removing the higher order
193 processing). Could the inefficient eye movement patterns reported in DD be transposed to a
194 reading deficit in another vulnerable population? To find answers to this question, we focused
195 on neurofibromatosis type 1 (NF1), that is a genetic disease in which a high prevalence of
196 reading deficits has been shown (between 30 % to 80 %; Arnold et al., 2020; Chaix et al.,
197 2017; Hyman et al., 2005), with a profound impact on their academic achievement (Krab et
198 al., 2008). In this neurodevelopmental disorder, visual-processing deficits were also
199 demonstrated (e.g., Hyman et al., 2005; Ribeiro et al., 2012; Vernet et al., 2022) and a first
200 eye-tracking study showed atypicality in the saccadic system (Lasker et al., 2003). Some
201 studies have suggested a delay in the maturation of low-level vision processes in children with
202 NF1 (Lasker et al., 2003; Ribeiro et al., 2012). To our knowledge, no study has investigated
203 the involvement of eye-movement control in the reading difficulties observed in NF1
204 children.

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

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

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

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

236

237 **2. METHOD**

238 **2.1. Participants**

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

241 The inclusion criteria were the same as those described in the study by Vernet et al.
242 (2022). All children were between 8 and 12 years old and attended school from grades 2
243 through 6. They were all French native speakers, right-handed and presented normal or
244 corrected-to-normal vision. There were no significant differences between groups for
245 chronological age (TD mean age = 118.30 months, SD = 11.48; DD mean age = 120.90
246 months, SD = 14.18; NF1: mean age = 121.57 months, SD = 18.68). All children underwent a
247 complete medical and neuropsychological screening. Children were excluded from the study
248 if they had Attention Deficit Hyperactivity Disorder (i.e., more than 6 symptoms of
249 Hyperactivity and/or Inattention in a parent rating on the DSM-5 diagnosis criteria),
250 intellectual disability (i.e., WISC total IQ below 70 and/or standard score below 7 on the
251 Similarities and/or Picture Concepts subtests), neurological or psychiatric disorder (e.g.,
252 epilepsy, brain tumor, or autism), or a known hearing impairment.

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

258 on the Alouette-test (Lefavrais, 2005) and on the ODEDYS-2 test (Jacquier-Roux et al.,
259 2002)). As expected, statistical analyses revealed that the DD group displayed significantly
260 poorer performances than the TD group for the three reading indices with large effect sizes
261 [reading age: $t(39) = -10.022$, $p < .001$, $d = -3.131$; reading accuracy: $t(39) = -5.703$, $p < .001$,
262 $d = -1.782$; reading fluency: $t(39) = -11.277$, $p < .001$, $d = -3.523$].

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

267 The French ethics committee Review Board approved the study (2014-A01239-38 and
268 2014-A01960-47), which was conducted according to the guidelines of the Declaration of
269 Helsinki (World Health Organisation, 2008). The written informed consent was obtained from
270 every participant and their legal tutors prior to inclusion in the study. Note that this study
271 included participants from a larger study examining procedural learning and memory¹.

272

273 **2.2. Material**

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

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

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

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

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

301 **2.3. Apparatus and procedure**

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

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

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

316 Before the experiment, a calibration step of the eye tracker was performed according to
317 a 9-point grid extended to the whole computer screen. The eye tracker was connected to a
318 Dell D-type docking station and a Dell Latitude D600 laptop computer for data recording and
319 stimulus delivery. The stimuli were displayed in white lowercase letters against a black
320 background in 22-point Courier New font, using a 14-inch colour monitor, at a resolution of
321 1400×1050 pixels. Participants were seated in front of the screen at 60 cm. At this distance,
322 one letter subtended a visual angle of 0.38° and 1° is equal to 0.95 cm. The space between
323 letters was 1 mm that corresponds to 2.8 pt or 0.09° .

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

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

333 **[Insert Figure 1 About here]**

334

335 **2.4. Data analysis**

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

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

351 **2.5. Statistical analysis**

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

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

357 In a second analysis, the same ANOVA were performed within the NF1 group, to better
358 understand the factors that determine the saccade targeting strategy implemented by children
359 with RD. Based on their performance on the Alouette test, NF1 children who presented
360 reading disorders (i.e., NF1RD; at least 12 months delay in reading age on the Alouette test
361 compared to chronological age) were compared to NF1 children without reading disorders
362 (i.e., NF1noRD). Note that 11 children were included in the NF1RD group and 9 in the
363 NF1noRD group. The two groups differed significantly in terms of reading age [$t(18) = -$
364 4.435, $p < .001$], reading accuracy [$t(18) = -4.144$, $p < .001$] and reading speed [$t(18) = -$
365 5.218, $p < .001$]².

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

373

374 **3. RESULTS**

375 **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 ($\chi^2 = 0.669$, $p > .05$).

376

[Insert Table 1 about here]

377

3.1.1. Saccade Size

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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].

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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).

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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 \times 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).

424 In order to examine whether symmetrical patterns were associated with short latencies
425 (saccades aim to target the centre of the word but undershoot their goal) and asymmetrical
426 patterns with long latencies (the eyes land at the location that enables maximum information
427 intake), we calculated (1) an asymmetry index (the difference between the mean amplitude of
428 a child initial saccades in the left and right VFs) and (2) a rapidity index (his or her mean
429 saccade latency, for leftward and rightward saccades) for each participant and each type of
430 target. The correlation between these two indices was not significant with a lack of correlation
431 for words [$r(39) = .05, p > .10$], strings of hashes [$r(39) = -.03, p > .10$] and solid lines [$r(39)$
432 $= .07, p > .10$]. The same tendency was found when separate analyses were made for TD and
433 DD children [$r(18) = -.19, p > .10$, and $r(19) = .40, p > .05$, respectively].

434 **3.1.3. Refixation probability**

435 We found a significant effect of group on refixation probability, [$F(1,38) = 6.626, p =$
436 $.014, \eta_p^2 = .148$], with surprisingly DD children making less refixations (57.64%) than TD
437 children (68.09%). There was also an interaction between presentation side and group
438 [$F(1,38) = 9.442, p = .004, \eta_p^2 = .199$], with an “adverse” effect of fixating the RVF among
439 the DD children (as compared to the TD group). Interestingly, the analyses revealed three-
440 way interaction between the group, the presentation side and the type of stimulus [$F(2,76) =$
441 $3.632, p = .031, \eta_p^2 = .087$]. Separate analyses were done for TD and DD children and
442 revealed that the interaction between presentation side and stimulus type was only significant
443 in TD children [$F(2,38) = 3.333, p = .046, \eta_p^2 = .149$ and $F < 1$, for TD and DD children
444 respectively]. For the DD group analysis, we only found a main effect of the side of
445 presentation [$F(1,19) = 9.005, p < .007, \eta_p^2 = .322$], with children making more refixations on
446 the RVF (64%) than on the LVF (51%). For the TD group, pairwise comparisons revealed a
447 significant difference between RVF and LVF for words only [$F(1,38) = 8.725, p < .01$ for
448 words, and $F_s < 1$ for strings of hashes and solid lines], thus suggesting an advantage for the

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

453

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

472

473 **3.2. Comparisons of NF1 children with and without RD**

474

[Insert Table 2 about here]

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3.2.1. Saccade size

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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).

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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 [$t(39) = -3.241, p < .01$].

487

[Insert Figure 2 about here]

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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].

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

506 **[Insert Figure 3 about here]**

507 The children with NF1noRD showed fully developed oculomotor mechanisms for
508 efficient reading similar to those of TD children [$F < 1$], with a clear PVL located to the left
509 of the word's centre in both visual fields for the 2 groups [$F < 1$, for the group \times presentation
510 side \times stimulus type interaction], and fine-tuned saccade targeting guided by the between-
511 character space information. The stimulus-type by presentation-side interaction [$F(2, 54) =$
512 $8.088, p < .001, \eta_p^2 = 0.231$] was explained by the strong difference between ILPs
513 distributions in discrete stimuli (words and strings of hashes) vs. continuous stimuli (solid
514 lines) [$F(1,54) = 10.08, p < .01$], the difference between words and strings of hashes being
515 non-significant [$F < 1$].

516 **3.2.2. Latency**

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

520 latencies for discrete stimuli than for continuous stimuli [$F(1,20) = 38.620, p < .001$ and
521 $F(1,16) = 101.705, p < .001$, for NF1RD and NF1noRD respectively].

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

531 **3.2.3. Refixation probability**

532 We found a significant interaction between stimulus type and presentation side, for both
533 groups of NF1 [$F(2,20) = 3.569, p = .047, \eta_p^2 = 0.263$ and $F(2,16) = 3.639, p = .050, \eta_p^2 =$
534 $.313$ for NF1RD and NF1noRD respectively]. In line with what had previously been observed
535 for TD children, pairwise comparisons in the NF1noRD group revealed a significant effect of
536 the VF for words on the refixation probability [$F(1,16) = 10.156, p < .005$ for words, and no
537 VF difference for strings of hashes and solid lines, $F_s < 1$]. For the NF1RD group, pairwise
538 comparisons yielded an opposite effect, with children performing more refixation on words in
539 the RVF [$F(1,20) = 9.028, p < .01$ for words and $F_s < 1$ for strings of hashes and solid lines].

540 When pooling the data of NF1noRD and TD children, this interaction remained [$F(2,54)$
541 $= 4.666, p = .014, \eta_p^2 = 0.153$], and could be entirely explained by a larger VF asymmetry for
542 words [$F(1,54) = 20.643, p < .001$ for words, and $F_s < 1$ for strings of hashes and solid lines].
543 Note that this larger VF asymmetry for words also resulted in a larger “linguistic” effect in

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

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

566

567 3.3. Cross-population results

568 Each child was assigned an ILP index (their initial-landing position for words in the
569 RVF) and a reading level index (their reading age³). The correlations between these two
570 measures are displayed in Figure 4. We found a significant correlation between reading age
571 and the initial landing position at P2 [$r(59) = .493, p < .001$], with a higher reading level being
572 associated with a higher probability to land first at the PVL (i.e., P2). A significant negative
573 correlation was also found between reading age and the initial landing position at P1 [$r(59) = -$
574 $.266, p < .05$], suggesting that poor readers are more likely to land at the beginning of the
575 word. Note that no significant correlation was shown for landing positions at P3 [$r(59) = -$
576 $.136, p > .05$].

577 **[Insert Figure 4. about here]**

578 Cluster analyses with a three-group solution yielded a relatively distinct separation of
579 participants into clusters with very little overlap. Figure 5 shows the three clusters of
580 participants for the distribution of the ILP frequency at each position and the relationship
581 between reading level and ILP. This allowed for an evaluation of the ways in which our
582 readers are similar or different in reading skills and eye movement behaviour. This analysis
583 strategy is supported by the idea that, as word identification becomes more efficient, children
584 shift from a letter-by-letter sequential decoding strategy (characterised by ILPs close to the
585 word beginning to be able to scan it from left to right) to more parallel processing (with ILPs
586 shifted toward the word centre (see also, Ablinger et al., 2013; Schattka et al., 2010). Cluster
587 2 comprised almost half of the participants (46%, mainly children without RD) and
588 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 differed⁵ 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.

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

613 **[Insert Figure 5 about here]**

614

615 **4. DISCUSSION**

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

622

623 **4.1. What determines where children first fixate?**

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

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

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

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

660

661 **4.2. How reading ability affects eye movement behaviour?**

662 A major aim of the present study was to determine whether reading level and changes in
663 written language experience over the course of DD, NF1 and TD children's developmental
664 trajectory are associated with changes in reading strategies, as indexed by saccade targeting
665 strategies. Firstly, the individual distributions of first fixation positions were modulated by
666 reading skills. Cluster analyses confirmed that the landing position of eye movement saccades
667 on words is a sensitive index of reading efficiency (Ducrot et al., 2013; Joseph et al., 2009;
668 Juhasz et al., 2008), with three subgroups of readers using different saccade targeting
669 strategies, irrespective of whether they have been classified as neurotypical, dyslexic or NF1.
670 Good readers (cluster 2) made their first fixation most of the time at the PVL whereas, in
671 children with poor reading skills, ILPs either occurred at the beginning of the word (cluster 1)
672 or covered a wider area around the centre of the word with high variability (cluster 3). A
673 convincing explanation for these saccade targeting differences is based on the dual-route
674 model of reading (Coltheart et al., 2001). As experience with written language grows, children
675 shift from a letter-by-letter sublexical decoding strategy to more parallel lexical processing
676 (Frith, 1985). In that sense, Tydgat and Grainger (2009) suggested that as children develop
677 their capacity to perform parallel letter processing, their ILPs shift from being close to the
678 beginning of words toward a position closer to the centre of words (see also Huestegge et al.,
679 2009). Meanwhile, visuo-attentional abilities would gradually develop with reading
680 experience (Bosse & Valdois, 2009; Hawelka & Wimmer, 2005). In that vein, children show
681 a smaller span of effective vision than adults (Häikiö et al., 2009; Rayner, 1986), the size of

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

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

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

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

714

715 **4.3. A Causal Role for Inefficient Eye Movements in Reading Disability?**

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

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

731 were able to accurately perceive and use parafoveal visual information in order to guide their
732 eyes during text reading, at least in the usual reading direction. However, they revealed a
733 greater difficulty in reaching the centre of targets presented in the LVF due to the greater
734 distance and an unusual reading direction. McKeben et al. (2004) have previously shown that
735 “a mechanism for adapting the gain of reactive, stimulus-triggered saccades (Deubel, 1995)
736 was active during reading in dyslexics, but that it was quantitatively less developed” (p. 396).
737 Moreover, RD children didn’t show the classical asymmetrical landing position pattern for
738 “linguistic-like” stimuli (with inter-character spaces). This suggests that in poor readers, the
739 preprocessing mechanism that detects the presence or absence of spaces between characters
740 and responsible for the direction of attentional scanning is not entirely operational, in
741 particular for the LVF. This result could be interpreted as a deficient allocation of visual
742 attention in RD children hampering the exact planning of fine-tuned leftward saccades (e.g.,
743 Facoetti, 2012; Facoetti et al., 2010; Lobier et al., 2012; Valdois et al., 2004; see Gavril et al.,
744 2021 for a meta-analysis). In that sense, it was reported that the orienting visuospatial
745 attention is impaired in dyslexia with a LVF “mini-neglect” and a RVF over-distractibility
746 (Facoetti, 2001; Hari, 2001; Hari & Renvall, 2001). The similar pattern of results for RD and
747 beginning readers (i.e., ILPs determined by the linguistic nature of stimuli instead of the
748 presence of inter-character spaces; Bellocchi, et al., 2013) speaks against this view. We rather
749 suggest that the lack of sensibility to the discreteness of the stimuli we observed in RD
750 children in the saccade computation, reflects their reading difficulties and/or a lack of
751 experience with written language (see also Hawelka et al., 2006). The cluster analyses support
752 this idea with children of cluster 1 (with the lowest reading level scores) showing an immature
753 saccade targeting strategy (characterised by ILPs near the words’ beginning and sequential
754 reading), which mirrors their poor reading skills. That goes in line with the above findings on
755 the asymmetry of the saccade extent and the data of Franzen et al. (2021) showing “a

756 laborious and more effortful reading strategy in DD, resembling a pattern observed in
757 beginning and poorer readers” (Franzen et al., 2021, p. 9, see also Ashby et al., 2005; Rayner,
758 1998). These findings can be accounted for by assuming that visual attention distribution (as
759 expressed by ILP) adapts to the differences in reading experience. Therefore, an important
760 result to retain from our study is that eye movements per se are not a cause of dyslexia.

761 What about the children of cluster 3? They presented an intermediate reading level and
762 exhibits an increased variance in the saccade amplitudes resulting in a flattened and diffuse
763 LP-curve. According to Snell and Theeuwes (2020), a clean oculomotor behaviour is reflected
764 in a narrower spread of ILPs, around the PVL (as observed in experienced readers of the
765 cluster 2). ILP spreads in cluster 3 readers widened upon an increased number of positions.
766 Note that the cluster 3 comprised 70% of reading-disabled children (mainly DD).
767 Interestingly, it has been reported that individuals with DD demonstrate a more
768 distributed/diffused mode of attention and have difficulty in narrowing their focus of attention
769 (Facoetti et al., 2000, 2003; Franceschini et al., 2012). Such detrimental effect of the
770 increased variability in the ILPs received support from two recent studies (Franzen et al.,
771 2021; Rima & Schmid, 2021). Franzen et al. (2021) found an increased number of
772 unexpected/atypical saccades in readers with dyslexia, thus suggesting that their eyes
773 occasionally move to seemingly random places. Regarding the distribution of the children’s
774 ILPs in the cluster 3, it is conceivable that an increased oculomotor instability would result in
775 more spatial variability in ILPs. Taken together with the performance at the DEM-test, this
776 pattern of results may reveal possible occasional oculomotor control deficits in RD, as already
777 reported in previous studies (e.g., Freedman et al., 2017; Raghuram et al., 2018; Tiadi et al.,
778 2016; Vagge et al., 2015), which might arise from underlying visual-processing deficits, such
779 as visuo-attentional deficits (Facoetti et al., 2003, 2019; Franceschini et al., 2012, 2022;
780 Valdois et al., 2004; Vernet et al., 2022).

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

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

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

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

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830

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838

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843

844 DECLARATION OF COMPETING INTEREST

845 The authors have no conflicts of interest to disclose.

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- 1280

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 | | Saccade latency | | Refixation probability | |
|--------------------|----------------------|-------------|-----------------|----------------|------------------------|---------------|
| | Mean (SD) | | Mean (SD) | | 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) |

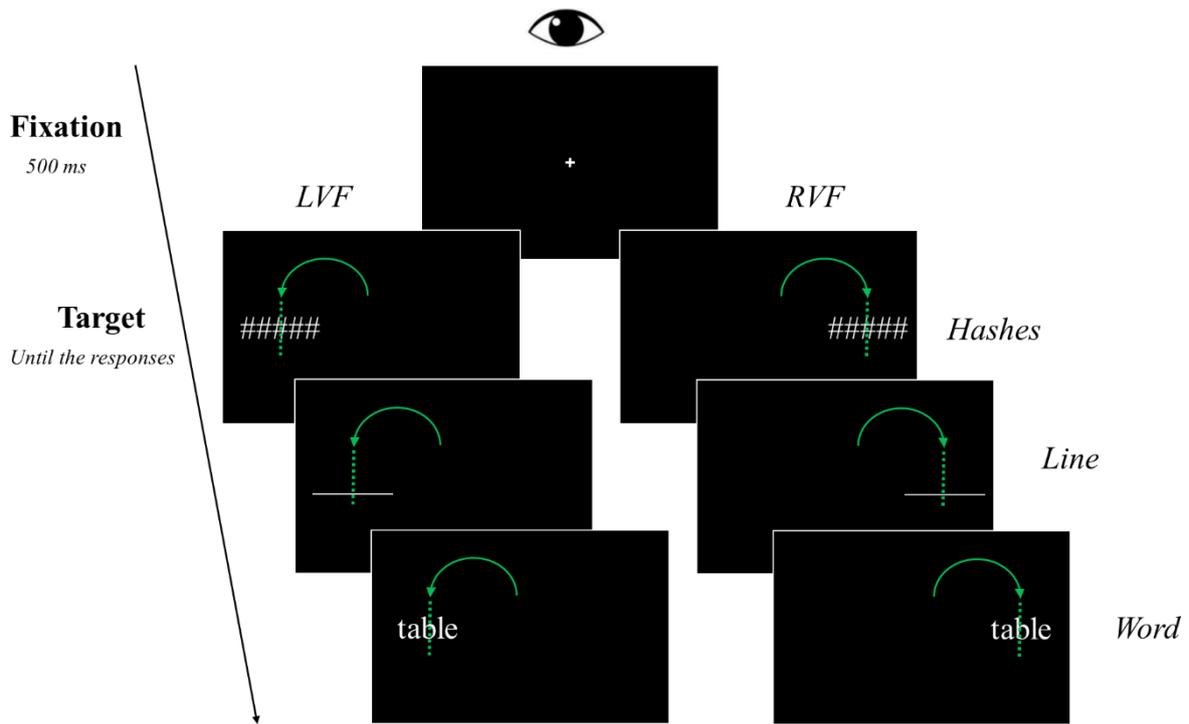
1284 *Notes.* Saccade size was measured according to the central fixation point. TD: typically
 1285 developing children; DD: children with developmental dyslexia.

1286

1287 Table 2. Mean of initial saccade size (in characters), saccade latency (in milliseconds) and
 1288 refixation probability (in percent) as a function of stimulus type, visual field, and group in
 1289 Experiment 2.

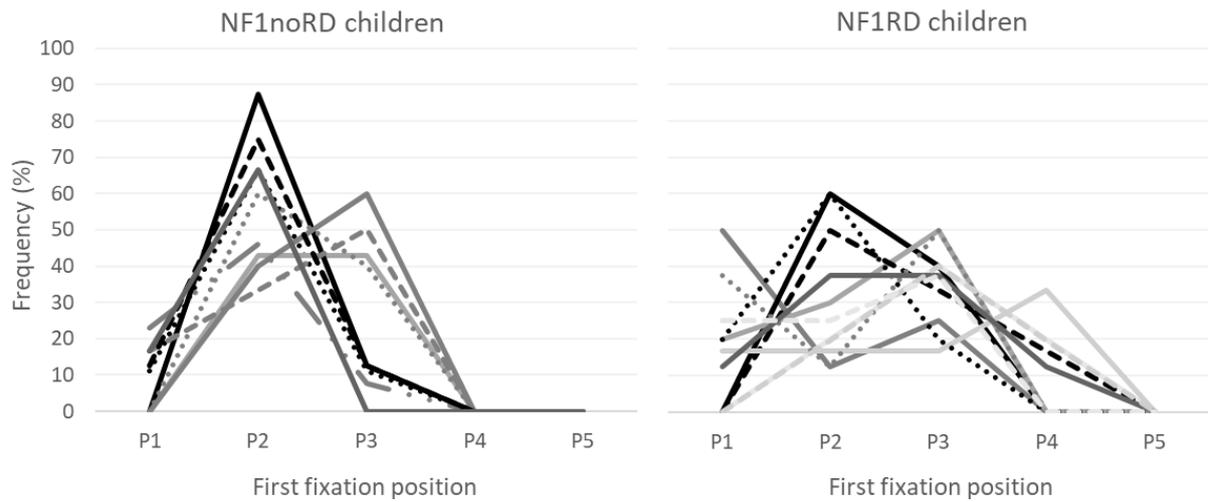
| | Initial saccade size | | Saccade latency | | Refixation probability | |
|--------------------|----------------------|-------------|-----------------|----------------|------------------------|---------------|
| | Mean (SD) | | Mean (SD) | | Mean (SD) | |
| | NF1noRD | NF1RD | NF1noRD | NF1RD | NF1noRD | 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) |

1290 *Notes.* Initial saccade size was measured according to the central fixation point. NF1RD: NF1
 1291 children with reading disorders; NF1noRD: NF1 children without reading disorders.



1292

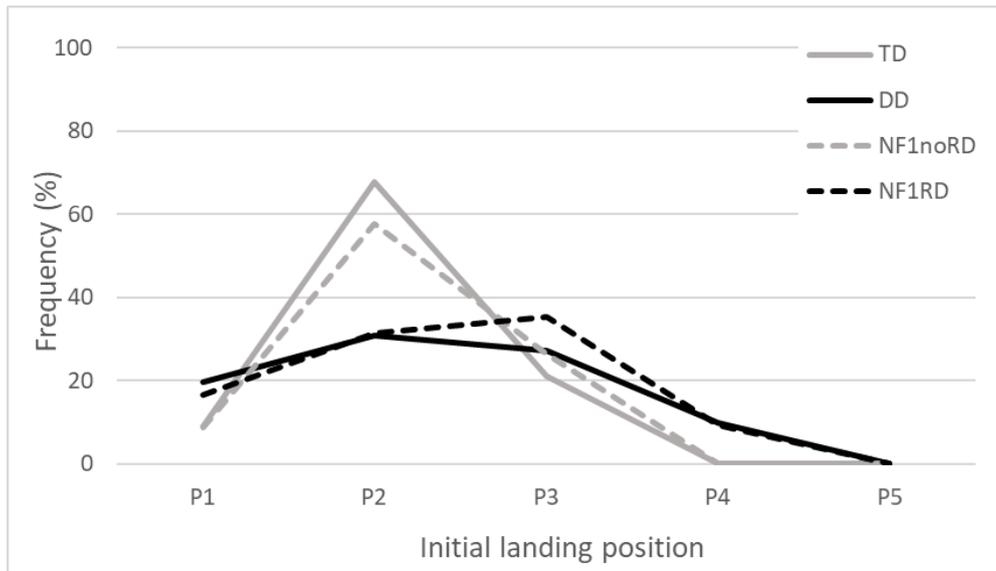
1293 Figure 1. Procedure used in the oculomotor lateralized bisection task. The different display
 1294 conditions of the stimuli are represented in this figure with the 3 types of stimuli (words,
 1295 hashes and lines) and the 2 visual fields of presentation (LVF and RVF). When the target item
 1296 appeared, participants were instructed to move their eyes to look at what they considered to be
 1297 the middle of the item (see arrows and dashed vertical lines in the figure).



1298

1299 Figure 2. Individual distribution of first fixation position specifically for words presented in
 1300 the RVF in NF1noRD (i.e., left part of the figure) and NF1RD (i.e., right part of the figure)
 1301 children.

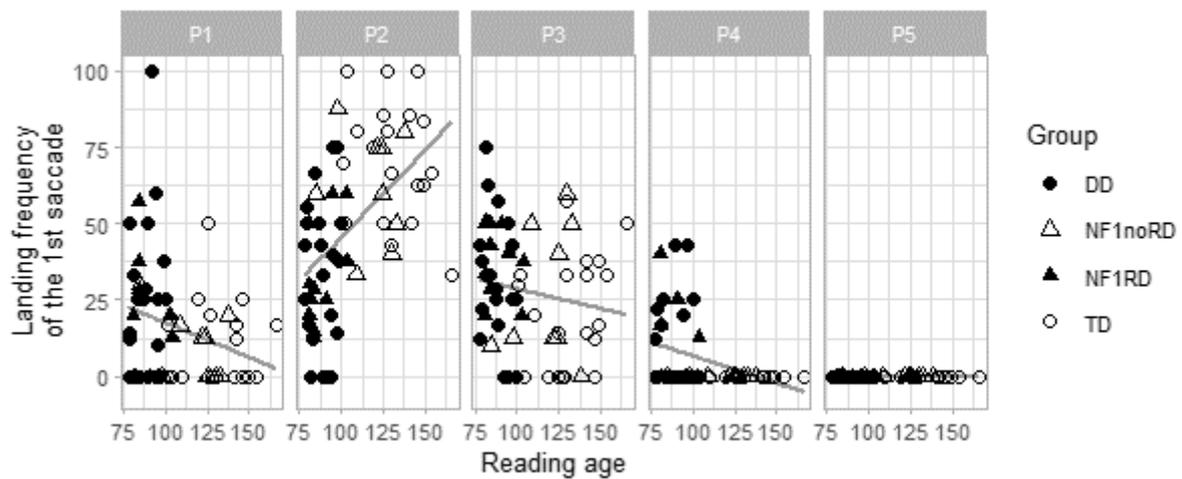
1302 *Notes.* This representation was made only for the words presented in the RVF to observe the
 1303 oculomotor behaviour in the most reading-like situation. Each line represents the individual
 1304 performance of a different participant. NF1RD: NF1 children with reading disorders;
 1305 NF1noRD: NF1 children without reading disorders.



1306

1307 Figure 3. Comparison of the initial landing position's frequency for words in the RVF
 1308 between the 4 groups of children in Experiment 1 and 2.

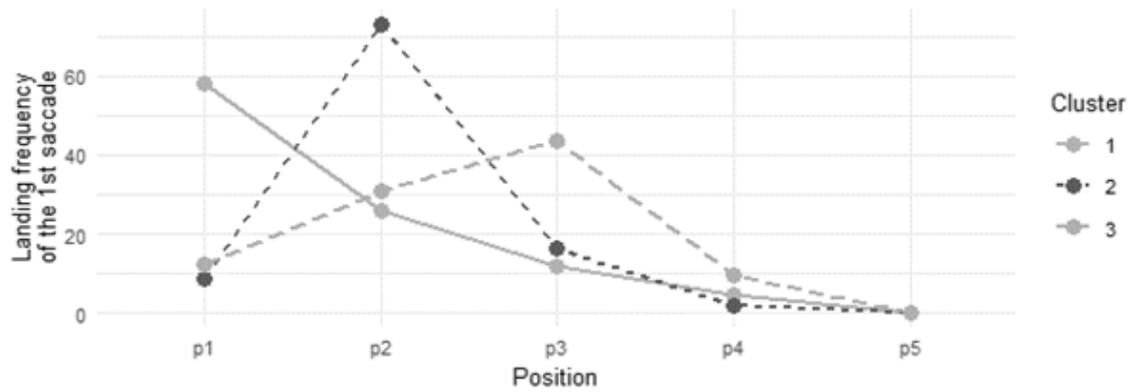
1309 *Notes.* This representation was made only for the words presented in the RVF to observe the
 1310 oculomotor behaviour in the most reading-like situation. TD: Typically developing children;
 1311 DD: children with developmental dyslexia; NF1RD: NF1 children with reading disorders;
 1312 NF1noRD: NF1 children without reading disorders.



1313

1314 Figure 4. Frequency of the initial landing of the first saccade (in percentage) at each position
 1315 of words according to reading age (in months) and groups.

1316 Notes. These representations were made only for the words presented in the RVF to observe
 1317 the oculomotor behaviour in the most reading-like situation. TD: Typically developing
 1318 children; DD: children with developmental dyslexia; NF1RD: NF1 children with reading
 1319 disorders; NF1noRD: NF1 children without reading disorders.



1320

1321 Figure 5. Distributions of the initial landing position (in percentage) according to the 3
 1322 clusters found for all groups combined.

1323 *Notes.* This figure was made only for the words presented in the RVF to observe the
 1324 oculomotor behaviour in the most reading-like situation.