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1 **Saccades and fixations in children with delayed reading skills**

2 **Running head: Eye movements in delayed reading skills**

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33 **Keywords:** eye movements, reading, children, saccades, fixation

34 **Abstract**

35 **Purpose:** Previous studies have reported that eye movements differ between
36 good/average and poor readers. However, these studies have been limited to
37 investigating eye movements during reading related tasks and thus, the differences
38 found could arise from deficits in higher cognitive processes involved in reading rather
39 than oculomotor performance. The purpose of the study is to determine the extent to
40 which eye movements in children with delayed reading skills are different to those
41 obtained from children with good/average reading skills in non-reading related tasks.

42 **Methods:** After a screening optometric assessment, eye movement recordings were
43 obtained from 120 children without delayed reading skills and 43 children with delayed
44 reading skills (4-11 years) using a Tobii TX300 eye tracker. Cartoon characters were
45 presented horizontally from -20° to $+20^{\circ}$ in steps of 5° to study saccades. An animated
46 stimulus in the center of the screen was presented for 8 seconds to study fixation
47 stability. Saccadic main sequences, and the number and amplitude of the saccades
48 during fixation were obtained for each participant. Children with delayed reading skills
49 ($n=43$) were unmasked after data collection was completed. Medians and quartiles were
50 calculated for each eye movement parameter for children without ($n=120$) and with
51 delayed ($n=43$) reading skills.

52 **Results:** Independent t-tests with Bonferroni correction showed no significant
53 differences in any of the saccadic main sequence parameters (Slope, Intercept, A, n and
54 Q ratio) between children without and with delayed reading ($p>0.01$). Similarly, no
55 significant differences were found in the number of saccades and their amplitude during
56 the fixation task between the two groups ($p>0.05$). Further, none of the gross optometric
57 parameters assessed (visual acuity, refractive error, ocular alignment, convergence,
58 stereopsis and accommodation accuracy) were found to be associated with delayed
59 reading skills ($p>0.05$).

60 **Conclusions:** Eye movements in children with delayed reading skills are quantitatively
61 similar to those found in children without delayed reading skills. These findings suggest
62 that in these children, delayed reading skills are not associated with eye movements and
63 further question interventions targeted at improving eye movement control.

64 **Introduction**

65 Typically, during reading, our eyes move along the lines of text by performing a series
66 of saccades of different amplitude and direction, interspaced with fixations of variable
67 duration. Generally, the saccades are forward saccades so the eyes move and fixate
68 from one word to the next, but they occasionally move backwards (regress) to re-fixate
69 a previous word or move to the following text line. Saccades and fixations are very
70 important components of reading as they provide the first step in extracting visual
71 information from the text and not surprisingly, there is an extensive literature
72 investigating saccadic eye movements and fixations in individuals with reading
73 difficulties.¹⁻⁷

74 Eye movement behaviour during reading is known to differ between good and poor
75 readers.^{e.g 1, 4, 6, 8, 9} Several early studies found that, during reading, non-skilled readers
76 show more fixations, longer fixation durations and more regressions than skilled
77 readers.^{1, 4, 6, 8, 9} Lefton et al. (1979)⁴ further reported an increased variability in the
78 number of saccades, number of fixations and the duration of fixation within a group of
79 poor readers compared to good readers of the same age. Perhaps the most interesting
80 finding was that, while good/average readers showed a very similar eye movement
81 strategy for each line of text (similar number of saccades and fixations and duration of
82 fixations), poor readers performed very differently in each line of text and paragraph.
83 Consequently, poor readers showed a relatively unstructured and disorganised eye
84 movement strategy during reading.⁴

85 Twenty-five years ago, the dominant view was that eye movements during reading were
86 independent of the linguistic and lexical characteristics of the text.¹⁰ Therefore, eye
87 movement disorders were often proposed to be the cause of delayed reading skills. Later
88 research has changed this view, and it is now clear that parameters such as fixation time
89 and the amplitude of saccades during reading are strongly influenced by the text
90 characteristics¹⁰ as well as the linguistic skills of the reader.¹¹ Hence, it can be argued
91 that the differences found in eye movements during reading in poor readers, can arise
92 from the text linguistic, syntactic and lexical characteristics or even from text difficulty
93 rather than from poor eye movement control or even from both. This argument might
94 be key in a child population, as children, especially those learning to read, are less

95 experienced with texts, are less familiar with the common words that adults tend to skip
96 when reading, and have a limited vocabulary compared to adults.

97 A few studies have evaluated saccades and fixations in individuals with delayed/poor
98 reading skills during non-reading tasks. Moreover, the results from these studies are
99 inconclusive as the findings have not been consistent. For instance, some studies^{12, 13}
100 have supported the early results from Pavlidis (1985)¹⁴ showing eye movement
101 differences in children with dyslexia and controls in non-reading eye movement tasks.
102 In contrast, other studies have shown no differences in eye movements during non-
103 reading tasks in individuals with dyslexia¹⁵⁻¹⁷ and poor readers^{2, 18} compared to age-
104 matched controls. Hence, the relationship between saccades, fixations and reading
105 performance remains unclear. It has already been proposed that oculomotor ability is
106 not the principal cause of reading difficulties,^{18, 19} and the multifactorial nature of
107 reading difficulties implies that saccadic control and/or fixation stability could be one,
108 but not the only, factor hampering reading in a population of poor readers.^{9, 19, 20}
109 Consistent with this, most studies assessing eye movements in poor readers have often
110 failed to obtain any optometric or vision measure other than the eye movement
111 recordings.^{e.g. 1, 2, 12, 14, 21} Visual aspects such as accommodation, refractive error and
112 vergence may interfere with reading performance.^{e.g. 22, 23} If these are not assessed, it
113 cannot be determined if they are also contributing to the reading problem in an
114 individual. Further, as most studies evaluating saccades and fixations in poor readers
115 have focussed on assessing these type of eye movements during reading tasks, it is
116 difficult to differentiate an atypical eye movement behaviour arising from oculomotor
117 control difficulties from one arising from the inherent text characteristics. Further
118 research is needed as studies evaluating saccades in children with dyslexia and delayed
119 reading during non-reading tasks have not yielded consistent findings.

120 Finally, it is not known how many children have delayed reading skills as a result of
121 poor oculomotor control. As a consequence, eye care professionals are frequently faced
122 with children considered to be at risk of eye movement difficulties, who are referred by
123 educational professionals (e.g. psychologists) and health care professionals (e.g.
124 occupational therapists and general practitioners) on the grounds of “poor tracking”,
125 skipping words and losing their place when reading.^{24, 25} The purpose of this study is to
126 investigate differences in saccades and fixations in non-reading based tasks (i.e. pure

127 oculomotor control tasks) between primary school age children without and with
128 delayed reading skills. The saccadic main sequence parameters were chosen to assess
129 saccadic performance as these provide information on the basic dynamics of the
130 saccadic eye movements. Saccadic main sequences have been studied in typically
131 developing children^{e.g. 26, 27} and atypical children^{e.g. 28, 29} but we are not aware of any
132 study investigating these in children with delayed reading. Saccadic latency and
133 variability were not studied here, as these have been suggested to provide information
134 on visual processing, but not on the actual quality of the saccades.³⁰ The number of
135 saccades (i.e. intrusive saccades) during the fixation task and the amplitude of such
136 saccades were chosen to quantify fixation stability, as these have been previously
137 studied in typically developing children,^{31, 32} and children with dyslexia.³³ The results
138 of the screening optometric test were compared as secondary outcomes. Our hypothesis
139 is that children with delayed reading skills have normal saccadic and fixation control
140 during non-reading related tasks. This hypothesis is based on the view that eye
141 movement performance during reading is largely influenced by the text characteristics,
142 and the linguistic skills of the reader. Therefore, abnormal eye movement behaviour
143 during reading in children with delayed reading skills is likely to indicate deficits
144 related to speech and language and not to oculomotor control deficits.

145 **Methods**

146 **Participants**

147 Invitation letters were posted to 11 schools in or near Cardiff. Two schools agreed to
148 take part. The protocol was approved by the Cardiff University School of Optometry
149 and Vision Sciences Ethics and Audit Committee and was designed in accordance with
150 the Declaration of Helsinki. Information sheets and consent forms were sent to all
151 parents, with the exception of parents of children with severe developmental disorders
152 such as autism and cerebral palsy. One school was city based with a multi-ethnic
153 population; the teachers selected 34 children from different age groups at random
154 whose parents consented to take part in the study. The teachers involved in the selection
155 of participants were not aware of the nature of the study until after the selection was
156 made, in order to avoid skewness of the sample. Only the children who were chosen by
157 the teacher were invited to participate. The other was a village school with a
158 predominantly Welsh population; the researcher chose one class per year group at

159 random and 135 children whose parents consented were recruited. Both schools are
160 situated within deprived areas and have a high percentage of free school meals (33%
161 and 32%; respectively). The demographic characteristics were determined by the
162 schools' willingness to participate; although deprived areas were not specifically
163 targeted, both schools were situated in such areas.

164 In total, 169 children participated (75 females and 94 males) ranging in age from 4 to
165 11 years. Figure 1 shows the age and gender distribution of the participants. The study
166 procedures, which include the screening optometric test and the eye movement
167 recording were conducted on the school premises, and each child participant completed
168 all tests on the same day.

169 **Children with delayed reading skills**

170 In the UK, children whose reading skills are below the expected level for their age are
171 assigned an Individual Educational Plan (IEP) and receive additional reading support
172 in school. There are other reasons for children having an IEP but this study was
173 concerned only with those having an IEP related to reading. The researchers were
174 masked regarding the IEPs of the child participants. After data analysis was complete,
175 the children's identities were coded, and a teacher of each school indicated by code
176 which children had an IEP related to delayed reading skills. A total of 43 children (25%;
177 14 females and 29 males) were identified as having an IEP related to delayed reading
178 skills: 6 (17%; 3 females and 3 males) from the first school and 37 from the second
179 school (27%; 11 females and 26 males). A sample size of 40 children with IEP provided
180 80% power to detect one standard deviation difference between the two groups of
181 children. The sample size and power was calculated at the end of the study using the
182 eye movement data from the children without delayed reading skills. This procedure
183 was conducted to verify the statistical power of the sample to detect differences
184 between both groups.

185 **Screening optometric assessment**

186 The principal investigator recorded the eye movements of all child participants, and
187 conducted the optometric assessment in 71% of the participants. The principal
188 investigator has wide experience in paediatric optometry and tests children routinely in
189 the Special Assessment Clinic, at Cardiff University. The rest of the optometric

190 assessments (29% of children) were conducted by three optometrists who were trained
191 by the principal investigator to perform the same procedures and recording methods.
192 The principal aim of the screening optometric assessment was to exclude any
193 participants with obvious optometric deficits that might affect a subject's ability to see
194 the eye movement targets clearly. A refractive error limit was also set as the quality of
195 the eye movement recordings can be influenced by high prescriptions in spectacle
196 correction. Hence, the inclusion criteria were logMAR visual acuity ≤ 0.3 with spectacle
197 correction if any, no strabismus or manifest refractive errors of more than 8D.

198 *Visual acuity*

199 Monocular and binocular distance visual acuity (VA) was measured at 3m using Kay
200 Pictures logMAR or Keeler logMAR charts. As these two tests have been found to be
201 comparable, each child was allowed to choose which of the two he/she preferred.³⁴
202 Monocular and binocular near VA was measured with the Kay Near test and the
203 Sonksen test. Monocular and binocular VA were measured with habitual spectacle
204 correction, if any. Lighting could not be controlled, but all testing in each school took
205 place in the same room, which was brightly lit.

206 The examiner occluded the left eye of the participant first with a pair of occluding
207 spectacles, positioned themselves 3m away from the child, and presented the first page
208 of the test. The child was asked to name or, alternatively, match each picture/letter of
209 the row of four. If three or more pictures/letters from a row were correctly named or
210 matched, the examiner presented the next smaller size until reaching the threshold. The
211 procedure was repeated occluding the right eye. To assess binocular VA, the examiner
212 presented the last line of pictures or letters that the child was able to see monocularly.
213 If three or more pictures or letters from that row were correctly named or matched, the
214 examiner presented the next smaller size and the procedure was repeated until reaching
215 the child's threshold in binocular conditions. Near VA was measured with the child's
216 preferred test (letters or pictures) at 33cm. Monocular and binocular VA at near were
217 measured in each participant using the same procedure described for measuring
218 distance VA.

219 *Refractive error*

220 Static distance retinoscopy was used to screen for evident refractive errors. Cycloplegic
221 retinoscopy was not feasible as the eye movement recordings could not have been
222 performed after dilation. Although Mohindra retinoscopy is the most appropriate
223 method for our study, this was not possible either as complete darkness could not be
224 achieved in the rooms that the schools made available for the study. The result was
225 recorded in sphero-cylinder form for cylinders over 1DC. If the cylinder was <1DC the
226 examiner recorded the spherical refractive error and noted the low cylinder.

227 *Ocular alignment*

228 Cover test was used to evaluate the presence of phorias and tropias at both distance and
229 near. The participants were asked to fixate on a cartoon picture placed on the wall 3m
230 away while the examiner assessed the presence of phorias and tropias. The same
231 procedure was performed for near while the participants fixated a picture on a fixation
232 stick placed 40cm away. The examiners made a judgment of the magnitude and
233 recovery of the phoria. The researcher recorded: ortho (when no movement of the eyes
234 was detected), and low, moderate or high esophoria/exophoria (or tropia) based on the
235 recovery and the direction of the movement.

236 *Objective Near Point of Convergence (NPC)*

237 Immediately after performing the near cover test, the participants were asked to keep
238 looking at the picture on the fixation stick at 40cm. The participants' attention was
239 attracted by asking him/her to look at a small detail from the picture and at the same
240 time, the examiner slowly moved the fixation stick towards the participants, while
241 observing the participants' vergence movement. Although the distance from the
242 convergence break point to the nose was measured with a tape measure, NPC was
243 recorded if >5cm, but simply noted as <5cm if the break point was very close. The
244 cutoff of 5cm was chosen in agreement with previously published literature on
245 normative values of NPC.³⁵

246 *Stereopsis*

247 A modified version of the Frisby stereotest that contains a demonstration plate was used
248 in our studies.³⁶ After presenting the demonstration plate, the examiner presented the
249 traditional Frisby plates beginning with the largest disparity plate. Each plate was
250 presented twice, and after each presentation, the examiner hid the plate behind his/her

251 back and rotated the plate, so the orientation of the random-dot circle was changed and
252 the same plate was presented. If the participant located the target on two consecutive
253 trials, the next plate (with decreasing disparity) was presented. The end point was
254 reached when the patient failed to locate the target. The testing distance was 40cm so
255 the disparities recorded were 340, 170 or 85sec arc for the first, second and third plate,
256 respectively.

257 *Accommodation*

258 The accuracy of accommodation was measured objectively as subjective methods to
259 determine accommodative function in children aged 4-11 years have been shown to be
260 challenging.³⁷ The examiner used dynamic retinoscopy to a target at 25cm using the
261 Ulster-Cardiff (UC) Cube. Questions about the illuminated picture on the UC-Cube
262 were asked during the task to stimulate accommodation and maintain the participant's
263 attention. The examiner began with the retinoscope alongside the target and evaluated
264 the retinoscopic reflex while the participant was looking at the target. If the reflex was
265 not neutral, the retinoscope was moved further away from (with reflex -
266 underaccommodating) or closer to (against reflex - overaccommodating) the child. The
267 dioptric difference between the target and the neutral reflex was recorded when a
268 lag/lead of more than 1.00D (i.e. outside the norms) was observed. If accommodation
269 was within the norms³⁸ ($\pm 1.00D$ from the UC-Cube position), the examiner recorded
270 "within the norms". The accommodative lag was measured in each eye while the child
271 looked at the UC-Cube binocularly.

272 **Eye movement recording**

273 Eye movement recordings were obtained in binocular conditions using the Tobii TX300
274 (Tobii AB, <http://www.tobii.com/>) eye tracker. This uses the Purkinje reflections to
275 establish horizontal and vertical eye position at 300Hz, with a maximum horizontal
276 gaze angle of $\pm 35^\circ$. The system gaze accuracy given by the manufacturer is $\pm 0.5^\circ$ for
277 monocular and $\pm 0.4^\circ$ for binocular conditions.³⁹

278 Children were seated at 65cm from the screen with their eyes in primary position and
279 facing the centre of the screen, with their habitual spectacle correction, if any. A
280 customised child-friendly head stabiliser was used for younger children to maintain
281 their head at a constant distance from the eye tracker/screen throughout. Older children

282 were instructed to keep their head still throughout the test. The eye tracker was
283 calibrated for each participant using the standard Tobii 5 point calibration in which a
284 target moved to 5 points on the screen: the geometric centre and the 4 corners. All test
285 stimuli were presented within the calibrated area.

286 *Saccades*

287 The stimuli used for eliciting saccades were 2° animal cartoons on a white background,
288 appearing at 5°, 10°, 15° and 20° amplitude to the left and to the right without gaps or
289 overlaps, that is, as each stimulus appeared, the previous one simultaneously
290 disappeared. Presentation order was randomised, and a total of 64 saccades were
291 elicited, 8 saccades for each amplitude and direction. Gellerman-Fellows sequences⁴⁰
292 were combined to avoid eliciting more than three consecutive saccades in the same
293 direction. The participants were instructed to look at the stimuli, but no further
294 instructions were given, so the task was as naturalistic as possible. The presentation
295 time was randomised, between 0.5 and 2 seconds. The task lasted a total of 1.5 minutes.

296 *Visual fixation*

297 The saccadic test was followed by the visual fixation test. A customised 2° animated
298 stimulus was placed in the centre of the screen on a white background. In this case, the
299 stimulus was stationary but continuously changed shape and colour while morphing
300 into different animal cartoons. The participants were instructed to keep looking at the
301 animated stimulus, which was presented for 8 seconds.

302 **Data Analysis**

303 The eye position traces were analysed offline using custom software written in
304 MATLAB (The Mathworks, Inc., <https://uk.mathworks.com/>). Eye velocity was
305 obtained by differentiating the eye position over time and smoothed with a 3 window
306 moving average filter, to reduce the additional noise arising from the differentiation
307 process.⁴¹

308 Saccades were automatically detected with the adaptive threshold algorithm described
309 by Behrens et al. (2010).⁴² The amplitude, duration and peak velocity of all the saccades
310 detected were calculated with a custom program written in MATLAB. The amplitude
311 and the duration of the saccades were obtained by subtracting the time and position at

312 the end of each saccade from the time and position of the start of each saccade detected.
313 The peak velocity was defined as the maximum velocity during the saccade. The
314 program obtained this parameter automatically by using an inbuilt MATLAB function
315 (Max). Only saccades with amplitudes above 4° were used for regression and statistical
316 analysis. Saccades with peak velocities above 700°/s, i.e. saccades larger than 20° (e.g.
317 child looking away) were considered an artefact and removed from the analysis.⁴³

318 *Saccadic main sequences*

319 Saccades show a unique feature, which is that they have a consistent relationship
320 between their peak velocity and amplitude as well as between their duration and
321 amplitude.⁴⁴ These relationships, known as saccadic main sequences, have been used
322 to characterise normal saccades, and they provide invaluable information regarding the
323 saccadic dynamics of an individual.⁴⁴ Moreover, saccadic main sequences have been
324 considered a very powerful tool to study saccades, their neurophysiological control,
325 and to determine whether the saccades of an individual are typical or abnormal.^{44, 45} For
326 that reason, main sequence *duration vs. amplitude*, *peak velocity vs. amplitude* and *peak*
327 *velocity x duration vs amplitude* were studied.

328 Three plots were obtained for the saccadic task for each child participant. The *duration*
329 *vs. amplitude* main sequence was obtained by plotting the amplitude (°) and the duration
330 (ms) of each saccade detected in the X and Y axis, respectively. The slope and intercept
331 obtained from a linear regression on that data were used for statistical purposes. This
332 equation of the linear regression usually has a slope between 2 and 2.7 and intercepts
333 ranging from 20 to 30 in typical adults.⁴⁵ Hence, higher values of the slope and intercept
334 indicate slow saccades. For the *peak velocity vs. amplitude* main sequence, the
335 amplitude and the peak velocity of each saccade detected were plotted in the X and Y
336 axis, respectively. A power fit was performed ($y=Ax^n$) for this main sequence for each
337 subject.⁴⁵ The parameters A and n from the power fit were used for statistical purposes.
338 High values found in the power fit parameters suggest abnormally high peak velocities
339 in the saccades. The *peak velocity x duration vs. amplitude* main sequence relationship
340 was plotted and a regression line constrained through the origin was fitted to obtain the
341 ratio Q from the slope of the fitted line.⁴⁶ The Q ratio has been suggested to be constant
342 of the order of 1.6-1.9 and values higher than 2 suggest the presence of an interruption
343 in the velocity profile of the saccades.⁴⁶

344 *Fixation stability*

345 The parameters analysed to assess fixation stability were the total number of saccades
346 during the 8 second fixation and their mean amplitude.

347 The saccades during the fixation task were detected using the algorithm previously
348 described. A custom written MATLAB program counted the number of saccades, and
349 calculated the mean amplitude of the saccades throughout the fixation task.

350 *Statistical analysis*

351 Statistical analyses were performed using SPSS Statistics for Windows version 20.0
352 (IBM Corp., <https://www.ibm.com/analytics/us/en/technology/spss/>). The distribution
353 of each optometric/eye movement parameter for each of the two reading ability groups
354 was assessed using histograms and Shapiro-Wilk tests. Parametric statistics were used
355 for VA and refractive error as these were normally distributed. Non-parametric tests
356 were used for the saccadic main sequence and fixation stability parameters as these
357 were non-normally distributed (Shapiro-Wilk $p < 0.05$ in $> 50\%$ of data for both groups).

358 *Optometric parameters*

359 A 2-factor ANOVA (with group as a major factor and accounting for the VA
360 measurements in each eye) was used to compare differences in VA and the absolute
361 spherical refractive error between children without and with delayed reading skills.

362 Contingency tables and Chi-square tests of independence incorporating Yates
363 correction of continuity were used to assess any association between delayed reading
364 and cylindrical refraction $> 1DC$, presence of phorias, lags of accommodation outside
365 of the norms ($> 1D$),³⁸ stereopsis $< 85''$ or NPC > 5 centimetres.

366 *Eye movements*

367 In order to determine whether the quality of the saccadic eye movements were different
368 between children without and with delayed reading skills, multiple Mann-Whitney tests
369 were performed. In order to avoid an increase in type I error,⁴⁷ a Bonferroni correction
370 was also performed and a p value < 0.01 was considered statistically significant. Two
371 non-parametric independent t-tests were performed to determine whether visual
372 fixation was significantly different between groups of children without and with

373 delayed reading skills. A Bonferroni correction was performed in order to control for
374 type I error and a p value <0.025 was considered to be statistically significant.

375 The analysis described above was used to evaluate differences in eye movement
376 behaviour between children without and with delayed reading. However, it could be
377 the case that some children with delayed reading have different eye movement
378 parameters to those found in children with good/average reading, but the differences
379 are not large enough to show a significant statistical effect between the two groups.
380 Hence, the upper and lower 95% confidence limits (Mean \pm 1.96* SD) were calculated
381 for each eye movement parameter for the group of children without delayed reading
382 skills. Then, the frequency of children without and with delayed reading who had one
383 or more eye movement parameters outside the 'normal' confidence limits was
384 evaluated. Chi-square test of independence incorporating Yates correction of continuity
385 were used to determine the existence of an association between delayed reading and
386 eye movement parameters outside the confidence intervals.

387 **Results**

388 Data from 2 children with nystagmus, 2 children with strabismus and from 2 children
389 in which the eye tracker was unable to calibrate were discarded from the analysis.
390 Hence, data from a total of 120 without delayed reading skills were analysed. No data
391 were discarded for the children with delayed reading skills (n=43).

392 **Optometric parameters**

393 Table 1 shows the mean VA and refractive error (absolute spherical refractive error)
394 found for the children without and with delayed reading skills. The same table presents
395 the statistical p values from the 2 factor ANOVA to compare differences between the
396 two groups. There were no significant differences in VA or the absolute spherical
397 refractive error between children without and with delayed reading. Chi-square tests
398 revealed no significant associations between delayed reading and cylindrical refractions
399 >1DC ($\chi^2=0$; $p=1.00$).

400 The distance cover test revealed that one child without delayed reading skills had a
401 distance phoria (high phoria) and 3 children with delayed reading skills had a distance
402 phoria (2 high and 1 moderate phorias). Near cover test revealed that 34 children

403 without delayed reading skills had near phorias (21 low, 3 moderate and 10 high
404 phorias) and 12 children with delayed reading skills had near phorias (8 low, 1 moderate
405 and 3 high phorias). Chi-square tests revealed no significant associations between
406 delayed reading skills and the presence of phorias (distance: $\chi^2=2.75$; $p=0.09$; near:
407 $\chi^2=0$; $p=1.00$). Moreover, the same test revealed no significant associations between
408 delayed reading skills and the presence of estimated high phorias (distance: $\chi^2=2.25$;
409 $p=0.11$; near: $\chi^2=0.08$; $p=0.77$).

410 Nine children without delayed reading skills and 4 children with delayed reading skills
411 had NPC >5cm. The mean NPC for children without and with delayed reading skills
412 and NPC >5cm was 7.11cm and 7.25cm, respectively. Accommodation was found
413 inaccurate (lags/leads >1D) in 3 children without delayed reading skills (2 children
414 demonstrated a lag (mean 1.75D lag) and one child demonstrated a 1.50D lead), and in
415 3 children with delayed reading (3 children demonstrated a lag; mean 1.66D lag).

416 **Eye movement recording**

417 Successful eye movement recordings from 113 (94%) and 42 (97%) children without
418 and with delayed reading skills were obtained for the saccadic task, respectively. For
419 the fixation stability task, successful eye movement recordings were obtained from 114
420 (95%) and 41 (95%) of children without and with delayed reading, respectively.

421 *Saccades*

422 The mean duration vs. amplitude main sequence for children without and with delayed
423 reading are represented for illustration purposes in Figure 2. It can be observed that the
424 saccadic duration-amplitude relationship does not differ between children without and
425 with delayed reading skills. The median and the 25th and 75th quartiles for the duration
426 vs. amplitude main sequence parameters (slope and intercept) are presented in Table 2.
427 Mann-Whitney tests confirmed no difference in slope ($Z_{153}=-0.96$; $p=0.33$) or intercept
428 ($Z_{153}=-0.07$; $p=0.93$) between the two groups.

429 Similar results were found for the other main sequence functions: peak velocity vs.
430 amplitude and peak velocity x duration vs. amplitude. The functions overlap for both
431 groups and no evident differences were observed. Table 2 presents the median and the
432 25th and 75th quartiles for the peak velocity x duration vs. amplitude main sequence
433 parameters, and the Q ratio for the two groups of children. Mann-Whitney tests

434 confirmed no significant differences for any of the main sequence parameters A ($Z_{153}=-$
435 $0.12; p=0.90$), n ($Z_{153}=-0.76; p=0.44$), and Q ratio ($Z_{153}=-2.18; p=0.03$) between groups.

436 *Fixation stability*

437 Figure 3 shows the median number of saccades and their amplitude for children without
438 and with delayed reading skills. Mann-Whitney non-parametric statistical tests
439 confirmed no significant differences in the number of saccades ($Z_{153}=-0.73; p=0.46$)
440 and their mean amplitude ($Z_{153}=-0.72; p=0.47$) between both groups

441 *Individual comparisons between children with and without delayed reading skills*

442 One or more of the five main sequence parameters of children with delayed reading
443 were more frequently outside the 95% confidence limits for their age (21%) than was
444 the case for children without delayed reading (13%), but the difference was not
445 significant ($\chi^2=0.99; p=0.31$), and 20% and 39% of the main sequence parameters in
446 children without and with delayed reading, respectively, were below the 95%
447 confidence interval ($\chi^2=0.44; p=0.50$).

448 Similarly, there was no association between delayed reading and an increased number
449 or amplitude of saccades during the fixation stability task ($\chi^2=0.00; p=1.00$). Hence,
450 7% of children without and with delayed reading had one or both fixation stability
451 parameters outside the 95% confidence limits, and all these were above the norms
452 ($\chi^2=0.00; p=1.00$).

453 **Discussion**

454 Although it is well established that there are differences in eye movements during
455 reading between good/average readers and poor readers, debate continues about the
456 causality or the effect of oculomotor deficits in reading difficulties.^{e.g. 18, 19, 48} In general,
457 individuals with good/average reading skills make fewer fixations and regressions and
458 also fixations are briefer than in poor readers.^{e.g. 4, 6, 8, 9} However, it can be argued that
459 these differences might be related to text difficulty,^{7, 10} text format^{21, 48} or higher order
460 linguistic characteristics such as syntactic difficulty and/or plausibility^{21, 49} rather than
461 to oculomotor deficits. For that reason, findings from eye movement behaviour during
462 reading in individuals with different reading abilities should be cautiously interpreted,
463 because reading is a complex process that not only involves effective oculomotor

464 control but also requires an effective integration of sensory, perceptual and cognitive
465 information.⁵⁰ Consequently, an increased number of saccades or an increased fixation
466 duration during reading in children with delayed reading skills may indicate difficulties
467 in other visual or non-visual aspects rather than poor oculomotor control. Hence, this
468 study investigated the saccadic main sequences and fixation stability in children
469 without and with delayed reading skills during non-reading conditions in order to
470 provide a quantitative evaluation of “pure” oculomotor performance in these two
471 groups of children.

472 Our results showed that the saccadic main sequences obtained from children with
473 delayed reading skills were not different to those found in children without delayed
474 reading skills. In addition, the saccadic main sequences, which describe the relationship
475 between different saccadic features and are a widely accepted method to characterise
476 normal saccades, were shown to be typical in children without and with delayed reading
477 skills, and therefore describe "normal" saccadic control in both groups. Although
478 saccades described here were obtained using a very different saccadic task than those
479 presented in previous studies in children with delayed reading skills during non-reading
480 tasks^{2,19} our results are consistent with previous literature, further supporting no
481 differences in saccadic performance between children without and with delayed
482 reading.

483 Most studies investigating eye movements in individuals with delayed reading skills
484 during non-reading tasks have mainly focussed on saccades rather than fixations.
485 However, as fixations can also be considered an important part of the reading process,
486 this study has also investigated fixation stability. Although the number and amplitude
487 of saccades during fixation were the only parameters used to assess fixation stability,
488 these were not different between the groups studied. To our knowledge, this is the first
489 study to investigate fixation stability in children with delayed reading skills during a
490 non-reading task. Notwithstanding, there is a study that quantitatively evaluated
491 fixation stability in typical developing children³¹ and the number and amplitude of the
492 saccades reported here in both groups of children are similar to those reported by Ygge
493 et al. (2005),³¹ confirming that our child populations were not different from previously
494 studied samples.

495 Comparison across groups can mask differences in individual performance. For that
496 reason, eye movement parameters from each child were individually compared to the
497 norms (95% confidence limits) obtained from children without delayed reading skills.
498 As expected, some children without and with delayed reading have their eye
499 movements outside the norms, but there was no significant difference between the
500 groups. The schools were asked to indicate which participating children had IEP related
501 to delayed reading. Since IEP's are provided for children with a wide range of
502 difficulties, it is possible that some of the children had other conditions that could have
503 affected eye movements. However, no child had manifest motor difficulties and 2
504 children with nystagmus were excluded from the study. Children with developmental
505 disorders such as autism and cerebral palsy were also excluded from the study. Our
506 sample size allows to detect differences between groups of one standard deviation or
507 more. Therefore, if smaller differences between groups are considered clinically
508 important, a larger sample size is needed, but it could be argued that differences smaller
509 than one standard deviation are unlikely to be functional. Finally, the unwitting
510 inclusion of children with other conditions could possibly make the data more variable.
511 However, the medians and 25th/75th quartiles from both groups were very similar, so
512 this would not change the comparison between the groups.

513 Other than eye movement difficulties, vision problems such as refractive error and
514 accommodation or vergence deficits can also interfere with the reading process.
515 Moreover, while vision deficits may not be the main cause of reading difficulties,⁵¹ it
516 is reasonable to suggest that these play an important role in reading abilities. Hyperopic
517 refractive error has been found to be strongly correlated with delayed reading skills and
518 lower academic performance in children.^{51, 52} In addition, a recently published study
519 also found a correlation between astigmatism and reading difficulties.²³ Our purpose
520 was to determine eye movement differences between good and poor readers, not to
521 investigate subtle optometric differences. In our analysis, therefore, we concentrated on
522 gross optometric functions (such as reduced acuity, manifest hyperopia or
523 accommodative lag) that could have influenced performance on eye movement testing.
524 Our study did not find a significant difference in the spherical or cylindrical refractive
525 error between children without and with delayed reading. Non-cycloplegic retinoscopy
526 was performed in the current study, so hyperopia levels could have been under-
527 estimated. Finally, none of the optometric measures obtained including VA,

528 accommodation accuracy, estimated phorias and stereopsis were associated with
529 delayed reading. We cannot of course exclude other or more subtle functions that could
530 be contributing to poor reading, but we can, we believe, exclude eye movement control.
531 Although we anticipate controversy with regard to these results, they are in line with
532 those found by a number of authors.^{53, 54}

533 **Conclusion**

534 These findings provide additional evidence to support the view that in general, reading
535 difficulties are not associated with eye movement deficits, and further question
536 interventions that target the visual system, which are generally non-evidence based.

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545 **Disclosure**

546 JM Woodhouse has a financial conflict of interest in relation to the Ulster-Cardiff Cube.
547 The other authors report no conflicts of interest and have no proprietary interest in any
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Table 1. Mean monocular (RE - right eye; LE - left eye), distance (D) and near (N) VA (\pm SD), and mean absolute monocular spherical (SPH) refractive error (\pm SD) in children without and with delayed reading skills.

		RE	LE	RE	LE	RE	LE
		D.VA	D. VA	N.VA	N.VA	SPH	SPH
Children without delayed reading	Mean	0.02	0.02	0.01	0.01	0.67	0.71
	\pm SD	\pm 0.08	\pm 0.06	\pm 0.06	\pm 0.04	\pm 0.95	\pm 1.09
Children with delayed reading	Mean	0.04	0.02	0.00	0.00	0.58	0.54
	\pm SD	\pm 0.08	\pm 0.08	\pm 0.06	\pm 0.04	\pm 0.66	\pm 0.77
p		0.55		0.99		0.73	

Table 2. Main sequence parameters for children without and with delayed reading skills. Values are medians for all participants in each group with the corresponding 25th and 75th quartiles.

	Duration vs. Amplitude main sequence		Peak velocity vs. Amplitude main sequence		Peak velocity x duration vs. Amplitude main sequence
	Slope	Intercept	A	n	Q ratio
Children without delayed reading	2 (1.78-2.20)	27.98 (24.59-31.94)	140.28 (119.88-159.81)	0.39 (0.35-0.44)	1.61 (1.56-1.68)
Children with delayed reading	1.91 (1.62-2.22)	28.19 (24.08-31.66)	142.37 (116.08-165.14)	0.41 (0.35-0.45)	1.66 (1.66-1.73)
p	0.33	0.93	0.90	0.44	0.03

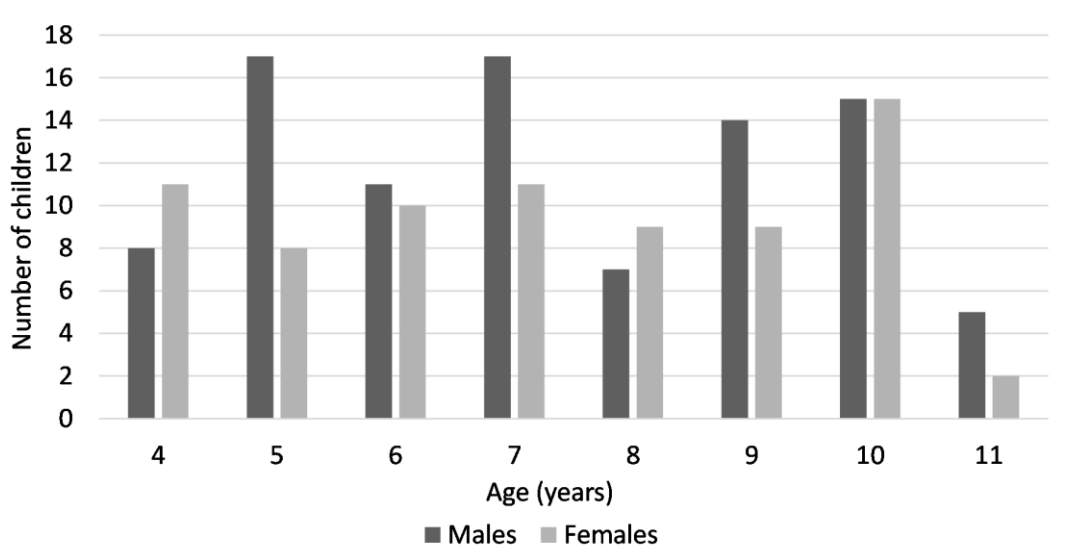


Figure 1. Histogram showing the age and gender distribution of the participants.

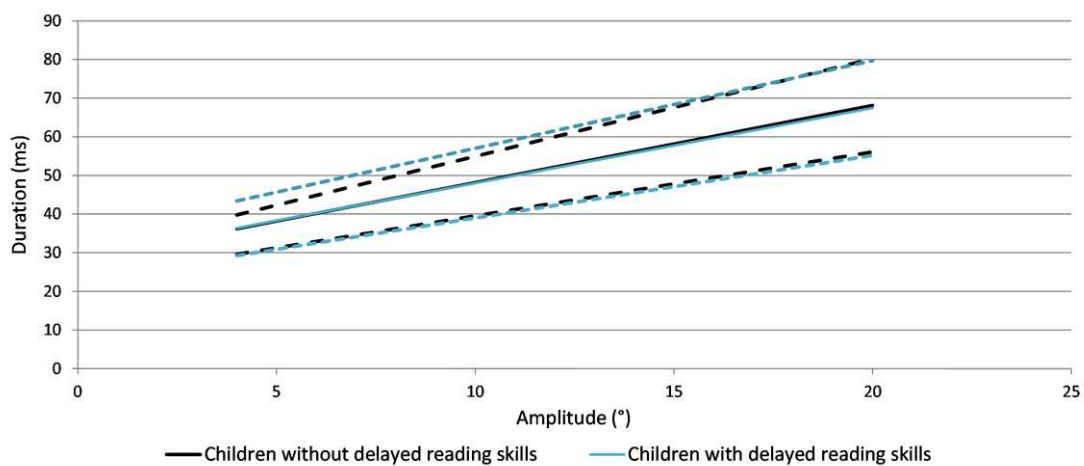


Figure 2. Duration vs. amplitude main sequence for children without and with delayed reading. The dashed line represents the mean duration vs. amplitude main sequence and the continuous lines represent \pm SD for each group.

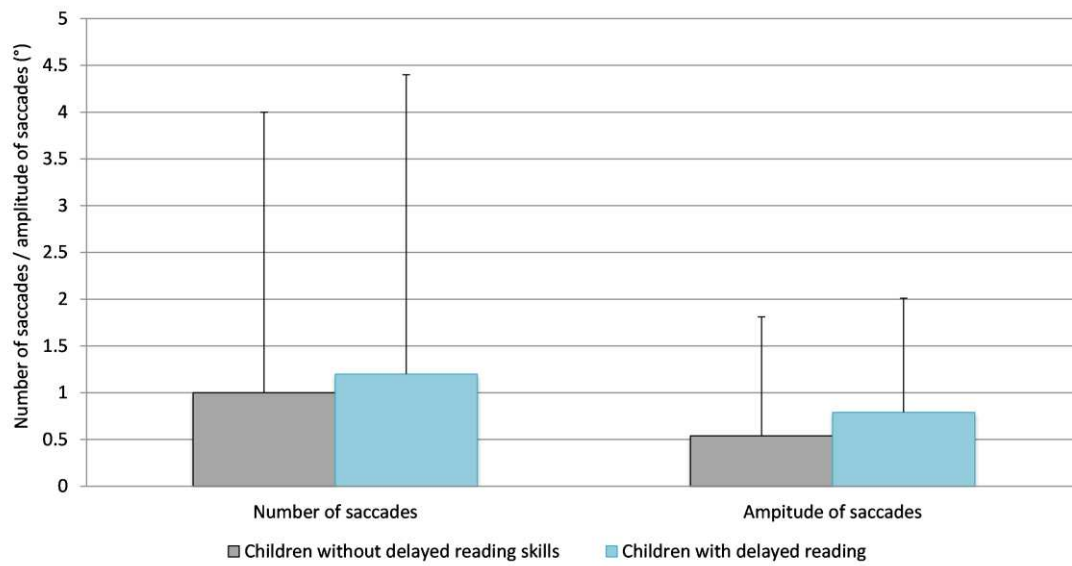


Figure 3. Fixation stability parameters for children without and with delayed reading skills. Values are medians for all participants in each group and the error bars represent the upper quartile (75th percentile).