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

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

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Abstract

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

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

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

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

Introduction

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

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

Twenty-five years ago, the dominant view was that eye movements during reading were independent of the linguistic and lexical characteristics of the text.[10] Therefore, eye movement disorders were often proposed to be the cause of delayed reading skills. Later research has changed this view, and it is now clear that parameters such as fixation time and the amplitude of saccades during reading are strongly influenced by the text characteristics[10] as well as the linguistic skills of the reader.[11] Hence, it can be argued that the differences found in eye movements during reading in poor readers, can arise from the text linguistic, syntactic and lexical characteristics or even from text difficulty rather than from poor eye movement control or even from both. This argument might 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 dyslexia[15-17] 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.

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.

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*

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

Ocular alignment

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

Objective Near Point of Convergence (NPC)

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

Stereopsis

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

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

Accommodation

The accuracy of accommodation was measured objectively as subjective methods to determine accommodative function in children aged 4-11 years have been shown to be challenging.[37] The examiner used dynamic retinoscopy to a target at 25cm using the Ulster-Cardiff (UC) Cube. Questions about the illuminated picture on the UC-Cube were asked during the task to stimulate accommodation and maintain the participant's attention. The examiner began with the retinoscope alongside the target and evaluated the retinoscopic reflex while the participant was looking at the target. If the reflex was not neutral, the retinoscope was moved further away from (with reflex - underaccommodating) or closer to (against reflex - overaccommodating) the child. The dioptric difference between the target and the neutral reflex was recorded when a lag/lead of more than 1.00D (i.e. outside the norms) was observed. If accommodation was within the norms[38] (± 1.00D from the UC-Cube position), the examiner recorded "within the norms". The accommodative lag was measured in each eye while the child looked at the UC-Cube binocularly.

Eye movement recording

Eye movement recordings were obtained in binocular conditions using the Tobii TX300 (Tobii AB, http://www.tobii.com/) eye tracker. This uses the Purkinje reflections to establish horizontal and vertical eye position at 300Hz, with a maximum horizontal gaze angle of ±35°. The system gaze accuracy given by the manufacturer is ±0.5° for monocular and ±0.4° for binocular conditions.[39]

Children were seated at 65cm from the screen with their eyes in primary position and facing the centre of the screen, with their habitual spectacle correction, if any. A customised child-friendly head stabiliser was used for younger children to maintain 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 2º animal cartoons on a white background,

288 appearing at 5º, 10º, 15º and 20º 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 sequences[40]

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 2º 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 4º were used for regression and statistical

316 analysis. Saccades with peak velocities above 700º/s, i.e. saccades larger than 20º (e.g.

317 child looking away) were considered an artefact and removed from the analysis.[43]

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, and

325 to determine whether the saccades of an individual are typical or abnormal.[44, 45] For that

326 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 d*uration*

329 *vs. amplitude* main sequence was obtained by plotting the amplitude (º) 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 Widnows 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 the
377 case that some children with delayed reading have different eye movement parameters
378 to those found in children with good/average reading, but the differences are not large
379 enough to show a significant statistical effect between the two groups. Hence, the upper
380 and lower 95% confidence limits (Mean ± 1.96* SD) were calculated for each eye
381 movement parameter for the group of children without delayed reading skills. Then, the
382 frequency of children without and with delayed reading who had one or more eye
383 movement parameters outside the 'normal' confidence limits was evaluated. Chi-
384 square test of independence incorporating Yates correction of continuity were used to
385 determine the existence of an association between delayed reading and eye movement
386 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: χ^2=2.75; p=0.09; near:

407   χ^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: χ^2=2.25;

409   p=0.11; near: χ^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 (χ^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 (χ^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 (χ^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 (χ^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 children[31] 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 $25^{th}/75^{th}$ 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]

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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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
548 of the materials mentioned in this article.

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Table 1. Mean monocular (RE - right eye; LE - left eye), distance (D) and near (N) VA (±SD), and mean absolute monocular spherical (SPH) refractive error (±SD) in children without and with delayed reading skills.

		RE D.VA	LE D. VA	RE N.VA	LE N.VA	RE SPH	LE SPH
Children without	Mean	0.02	0.02	0.01	0.01	0.67	0.71
delayed reading	±SD	±0.08	±0.06	±0.06	±0.04	±0.95	±1.09
Children with	Mean	0.04	0.02	0.00	0.00	0.58	0.54
delayed reading	±SD	±0.08	±0.08	±0.06	±0.04	±0.66	±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.

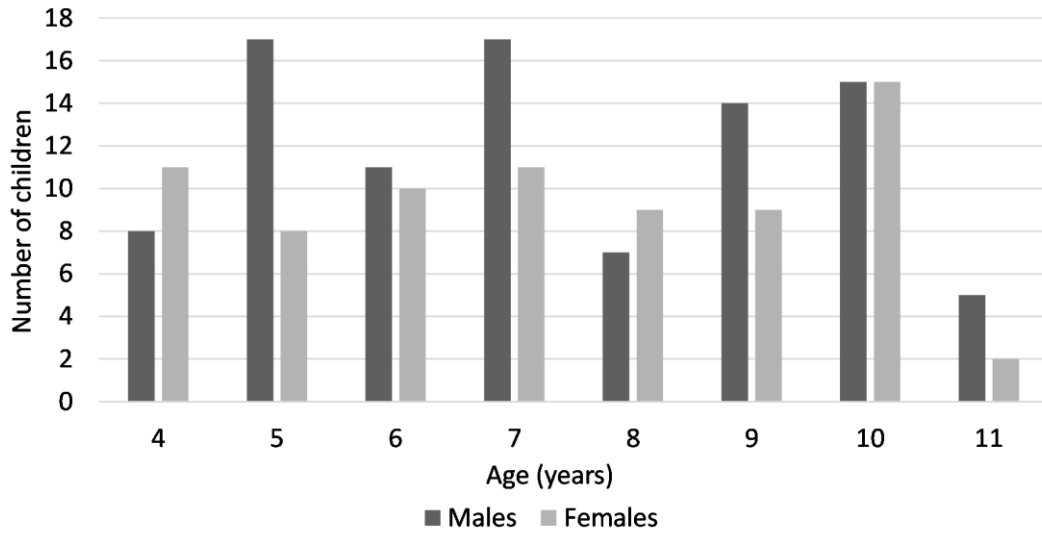|	Duration vs. Amplitude main sequence		Peak velocity vs. Amplitude main sequence		Peak velocity x duration vs. Amplitude main sequence
	Slope	Intercept	A	n	Q ratio
Children without delayed reading	2 (1.78-2.20)	27.98 (24.59-31.94)	140.28 (119.88-159.81)	0.39 (0.35-0.44)	1.61 (1.56-1.68)
Children with 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.
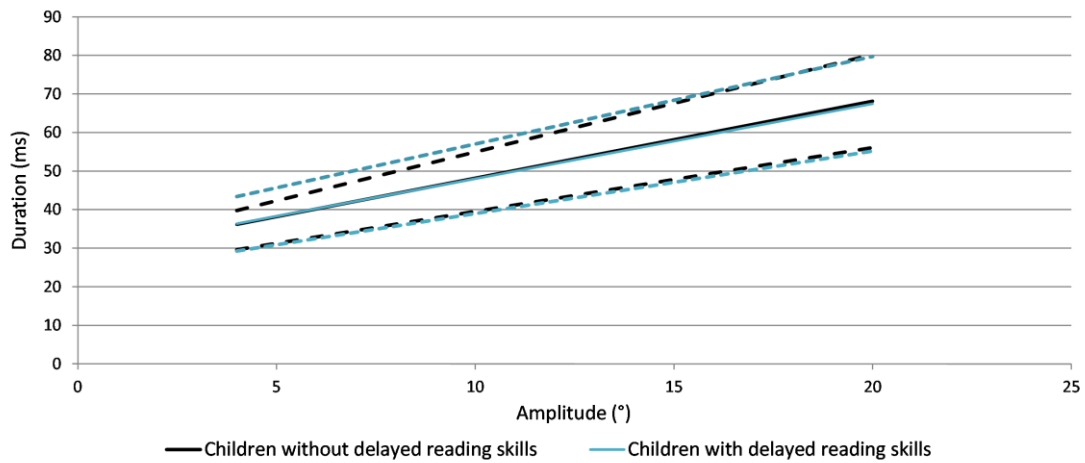

Figure 2. Duration vs. amplitude main sequence for children without and with delayed reading. The continuous lines represent the mean duration vs. amplitude main sequence and the discontinuous lines represent ±SD for each group.
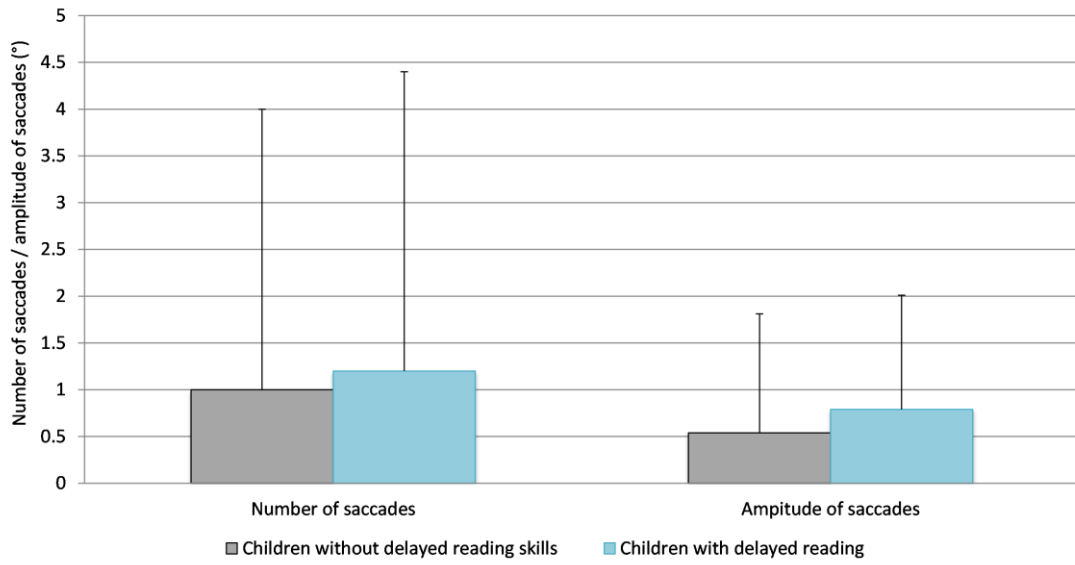
Figure 3. Fixation stability parameters for children without and with delayed reading skills. Values are medians for all participants in each group and the error bars represent the upper quartile (75th percentile).