Saccades and fixations in children with delayed reading skills

Running head: Eye movements in delayed reading skills

Authors: Valldeflors Vinuela-Navarro[1]; Jonathan T. Erichsen[1]; Cathy Williams[2]; J. Margaret Woodhouse[1]

[1]School of Optometry and Vision Sciences
Cardiff University
Maindy Road
Cardiff
CF24 4HQ
UK

[2]School of Social and Community Medicine
University of Bristol
Oakfield House
Oakfield Grove
Clifton
Bristol
BS8 2BN
UK

Correspondence to:
Dr Joy Margaret Woodhouse
School of Optometry and Vision Sciences
Cardiff University
Maindy Road
Cardiff
CF24 4HQ
UK
Phone: +44 (0)29 207 6522
Fax: +44 (0)29 2087 4859
Email: Woodhouse@cardiff.ac.uk

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

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

A few studies have evaluated saccades and fixations in individuals with delayed/poor reading skills during non-reading tasks. Moreover, the results from these studies are inconclusive as the findings have not been consistent. For instance, some studies [12, 13] have supported the early results from Pavlidis (1985)[14] showing eye movement differences in children with dyslexia and controls in non-reading eye movement tasks. In contrast, other studies have shown no differences in eye movements during non-reading tasks in individuals with dyslexia[15-17] and poor readers[2, 18] compared to age-matched controls. Hence, the relationship between saccades, fixations and reading performance remains unclear. It has already been proposed that oculomotor ability is not the principal cause of reading difficulties,[18, 19] and the multifactorial nature of reading difficulties implies that saccadic control and/or fixation stability could be one, but not the only, factor hampering reading in a population of poor readers.[9, 19, 20] Consistent with this, most studies assessing eye movements in poor readers have often failed to obtain any optometric or vision measure other than the eye movement recordings.[e.g. 1, 2, 12, 14, 21] Visual aspects such as accommodation, refractive error and vergence may interfere with reading performance.[e.g. 22, 23] If these are not assessed, it cannot be determined if they are also contributing to the reading problem in an individual. Further, as most studies evaluating saccades and fixations in poor readers have focussed on assessing these type of eye movements during reading tasks, it is difficult to differentiate an atypical eye movement behaviour arising from oculomotor control difficulties from one arising from the inherent text characteristics. Further research is needed as studies evaluating saccades in children with dyslexia and delayed reading during non-reading tasks have not yielded consistent findings.

Finally, it is not known how many children have delayed reading skills as a result of poor oculomotor control. As a consequence, eye care professionals are frequently faced with children considered to be at risk of eye movement difficulties, who are referred by educational professionals (e.g. psychologists) and health care professionals (e.g. occupational therapists and general practitioners) on the grounds of "poor tracking", skipping words and losing their place when reading.[24, 25] The purpose of this study is to investigate differences in saccades and fixations in non-reading based tasks (i.e. pure oculomotor control tasks) between primary school age children without and with delayed reading skills. The saccadic main sequence parameters were chosen to assess saccadic performance as these provide information on the basic dynamics of the saccadic eye movements. Saccadic main sequences have been studied in typically developing children[e.g. 26, 27] and atypical children[e.g. 28, 29] but we are not aware of any study investigating these in children with delayed reading. Saccadic latency and variability were not studied here, as these have been suggested to provide information on visual processing, but not on the actual quality of the saccades.[30] The number of saccades (i.e. intrusive saccades) during the fixation task and the amplitude of such saccades were chosen to quantify fixation stability, as these have been previously studied in typically developing children,[31, 32] and children with dyslexia.[33] The results of the screening optometric test were compared as secondary outcomes. Our hypothesis is that children with delayed reading skills have normal saccadic and fixation control during non-reading related tasks. This hypothesis is based on the view that eye movement performance during reading is largely influenced by the text characteristics, and the linguistic skills of the reader. Therefore, abnormal eye movement behaviour during reading in children with delayed reading skills is likely to indicate deficits related to speech and language and not to oculomotor control deficits.

Methods

Participants

Invitation letters were posted to 11 schools in or near Cardiff. Two schools agreed to take part. The protocol was approved by the Cardiff University School of Optometry and Vision Sciences Ethics and Audit Committee and was designed in accordance with the Declaration of Helsinki. Information sheets and consent forms were sent to all parents, with the exception of parents of children with severe developmental disorders such as autism and cerebral palsy. One school was city based with a multi-ethnic population; the teachers selected 34 children from different age groups at random whose parents consented to take part in the study. The teachers involved in the selection of participants were not aware of the nature of the study until after the selection was made, in order to avoid skewness of the sample. Only the children who were chosen by the teacher were invited to participate. The other was a village school with a predominantly Welsh population; the researcher chose one class per year group at random and 135 children whose parents consented were recruited. Both schools are situated within deprived areas and have a high percentage of free school meals (33% and 32%; respectively). The demographic characteristics were determined by the schools' willingness to participate; although deprived areas were not specifically targeted, both schools were situated in such areas.

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

Children with delayed reading skills

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

Screening optometric assessment

The principal investigator recorded the eye movements of all child participants, and conducted the optometric assessment in 71% of the participants. The principal investigator has wide experience in paediatric optometry and tests children routinely in the Special Assessment Clinic, at Cardiff University. The rest of the optometric assessments (29% of children) were conducted by three optometrists who were trained by the principal investigator to perform the same procedures and recording methods. The principal aim of the screening optometric assessment was to exclude any participants with obvious optometric deficits that might affect a subject's ability to see the eye movement targets clearly. A refractive error limit was also set as the quality of the eye movement recordings can be influenced by high prescriptions in spectacle correction. Hence, the inclusion criteria were logMAR visual acuity ≤0.3 with spectacle correction if any, no strabismus or manifest refractive errors of more than 8D.

Visual acuity

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

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

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 ±35º. The system gaze accuracy given by the manufacturer is ±0.5º for monocular and ±0.4º 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 were instructed to keep their head still throughout the test. The eye tracker was calibrated for each participant using the standard Tobii 5 point calibration in which a target moved to 5 points on the screen: the geometric centre and the 4 corners. All test stimuli were presented within the calibrated area.

Saccades

The stimuli used for eliciting saccades were 2º animal cartoons on a white background, appearing at 5º, 10º, 15º and 20º amplitude to the left and to the right without gaps or overlaps, that is, as each stimulus appeared, the previous one simultaneously disappeared. Presentation order was randomised, and a total of 64 saccades were elicited, 8 saccades for each amplitude and direction. Gellerman-Fellows sequences[40] were combined to avoid eliciting more than three consecutive saccades in the same direction. The participants were instructed to look at the stimuli, but no further instructions were given, so the task was as naturalistic as possible. The presentation time was randomised, between 0.5 and 2 seconds. The task lasted a total of 1.5 minutes.

Visual fixation

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

Data Analysis

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

Saccades were automatically detected with the adaptive threshold algorithm described by Behrens et al. (2010).[42] The amplitude, duration and peak velocity of all the saccades detected were calculated with a custom program written in MATLAB. The amplitude and the duration of the saccades were obtained by subtracting the time and position at the end of each saccade from the time and position of the start of each saccade detected. The peak velocity was defined as the maximum velocity during the saccade. The program obtained this parameter automatically by using an inbuilt MATLAB function (Max). Only saccades with amplitudes above 4º were used for regression and statistical analysis. Saccades with peak velocities above 700º/s, i.e. saccades larger than 20º (e.g. child looking away) were considered an artefact and removed from the analysis.[43]

Saccadic main sequences

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

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

Fixation stability

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

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

Statistical analysis

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

Optometric parameters

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

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

Eye movements

In order to determine whether the quality of the saccadic eye movements were different between children without and with delayed reading skills, multiple Mann-Whitney tests were performed. In order to avoid an increase in type I error,[47] a Bonferroni correction was also performed and a p value <0.01 was considered statistically significant. Two non-parametric independent t-tests were performed to determine whether visual fixation was significantly different between groups of children without and with delayed reading skills. A Bonferroni correction was performed in order to control for type I error and a p value <0.025 was considered to be statistically significant.

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

Results

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

Optometric parameters

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

The distance cover test revealed that one child without delayed reading skills had a distance phoria (high phoria) and 3 children with delayed reading skills had a distance phoria (2 high and 1 moderate phorias). Near cover test revealed that 34 children without delayed reading skills had near phorias (21 low, 3 moderate and 10 high phorias) and 12 children with delayed reading skills had near phorias (8 low, 1 moderate and 3 high phorias). Chi-square tests revealed no significant associations between delayed reading skills and the presence of phorias (distance: χ^2=2.75; p=0.09; near: χ^2=0; p=1.00). Moreover, the same test revealed no significant associations between delayed reading skills and the presence of estimated high phorias (distance: χ^2=2.25; p=0.11; near: χ^2=0.08; p=0.77).

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

Eye movement recording

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

Saccades

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

Similar results were found for the other main sequence functions: peak velocity vs. amplitude and peak velocity x duration vs. amplitude. The functions overlap for both groups and no evident differences were observed. Table 2 presents the median and the 25th and 75th quartiles for the peak velocity x duration vs. amplitude main sequence parameters, and the Q ratio for the two groups of children. Mann-Whitney tests confirmed no significant differences for any of the main sequence parameters A (Z_{153}=-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.

Fixation stability

Figure 3 shows the median number of saccades and their amplitude for children without and with delayed reading skills. Mann-Whitney non-parametric statistical tests confirmed no significant differences in the number of saccades (Z_{153}=-0.73; p=0. 46) and their mean amplitude (Z_{153}=-0.72; p=0.47) between both groups

Individual comparisons between children with and without delayed reading skills

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

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

Discussion

Although it is well established that there are differences in eye movements during reading between good/average readers and poor readers, debate continues about the causality or the effect of oculomotor deficits in reading difficulties.[e.g. 18, 19, 48] In general, individuals with good/average reading skills make fewer fixations and regressions and also fixations are briefer than in poor readers.[e.g. 4, 6, 8, 9] However, it can be argued that these differences might be related to text difficulty,[7, 10] text format[21, 48] or higher order linguistic characteristics such as syntactic difficulty and/or plausibility[21, 49] rather than to oculomotor deficits. For that reason, findings from eye movement behaviour during reading in individuals with different reading abilities should be cautiously interpreted, because reading is a complex process that not only involves effective oculomotor control but also requires an effective integration of sensory, perceptual and cognitive information.[50] Consequently, an increased number of saccades or an increased fixation duration during reading in children with delayed reading skills may indicate difficulties in other visual or non-visual aspects rather than poor oculomotor control. Hence, this study investigated the saccadic main sequences and fixation stability in children without and with delayed reading skills during non-reading conditions in order to provide a quantitative evaluation of "pure" oculomotor performance in these two groups of children.

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

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

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

Other than eye movement difficulties, vision problems such as refractive error and accommodation or vergence deficits can also interfere with the reading process. Moreover, while vision deficits may not be the main cause of reading difficulties,[51] it is reasonable to suggest that these play an important role in reading abilities. Hyperopic refractive error has been found to be strongly correlated with delayed reading skills and lower academic performance in children.[51, 52] In addition, a recently published study also found a correlation between astigmatism and reading difficulties.[23] Our purpose was to determine eye movement differences between good and poor readers, not to investigate subtle optometric differences. In our analysis, therefore, we concentrated on gross optometric functions (such as reduced acuity, manifest hyperopia or accommodative lag) that could have influenced performance on eye movement testing. Our study did not find a significant difference in the spherical or cylindrical refractive error between children without and with delayed reading. Non-cycloplegic retinoscopy was performed in the current study, so hyperopia levels could have been under-estimated. Finally, none of the optometric measures obtained including VA, accommodation accuracy, estimated phorias and stereopsis were associated with delayed reading. We cannot of course exclude other or more subtle functions that could be contributing to poor reading, but we can, we believe, exclude eye movement control. Although we anticipate controversy with regard to these results, they are in line with those found by a number of authors.[53, 54]

Conclusion

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

Acknowledgments

This work was supported by The College of Optometrists. Special thanks to the children who took part, their parents and their teachers from Kitchener Primary School and White Rose Primary School. We are grateful also to Prof Chris Harris (Plymouth University), Dr Rod Woodhouse (Cardiff University), Dr Matt Dunn (Cardiff University) for their support with data analysis and programming and Mr Chris Jones (Cardiff University), Mrs Louise Terry (Cardiff University) and Dr Beth Frost for their data collection support.

Disclosure

JM Woodhouse has a financial conflict of interest in relation to the Ulster-Cardiff Cube. The other authors report no conflicts of interest and have no proprietary interest in any of the materials mentioned in this article.

1. Powers M, Grisham D & Riles P. Saccadic tracking skills of poor readers in high school. Optometry 2008; 79: 228-234.
2. Black JL, Collins DW, De Roach JN & Zubrick S. A detailed study of sequential saccadic eye movements for normal- and poor-reading children. Percept Mot Skills 1984; 59: 423-434.
3. Bucci MP, Nassibi N, Gerard CL, Bui-Quoc E & Seassau M. Immaturity of the oculomotor saccade and vergence interaction in dyslexic children: evidence from a reading and visual search study. PLoS ONE 2012; 7: e33458, doi:10.1371/journal.pone.0033458.
4. Lefton LA, Nagle RJ, Johnson G & Fisher DF. Eye Movement Dynamics of Good and Poor Readers: Then and Now. J Lit Res 1979; 11: 319-328.
5. Solan HA. Eye movement problems in achieving readers: an update. Am J Optom Physiol Opt 1985; 62: 812-819.
6. Solan HA. Deficient eye-movement patterns in achieving high school students: three case histories. J Learn Disabil 1985; 18: 66-70.
7. Rayner K. Eye movements in reading and information processing: 20 years of research. Psychol Bull 1998; 124: 372-422.
8. Griffin DC, Walton HN & Ives V. Saccades as Related to Reading Disorders. J Learn Disabil 1974; 7: 310-316.
9. Poynter HL, Schor C, Haynes HM & Hirsch J. Oculomotor functions in reading disability. Am J Optom Physiol Opt 1982; 59: 116-127.
10. Rayner K & Liversedge S. Linguistic and cognitive influences on eye movements during reading. In: The Oxford handbook of eye movements (Liversedge S, Gilchrist I & Everling S, editors) Oxford University Press Inc: New York, 2011; pp. 751-766.
11. Kuperman V & Van Dyke JA. Effects of individual differences in verbal skills on eye-movement patterns during sentence reading. J of Mem Lang 2011; 65: 42-73.
12. Biscaldi M, Gezeck S & Stuhr V. Poor saccadic control correlates with dyslexia. Neuropsychologia 1998; 36: 1189-1202.
13. Bucci MP, Bremond-Gignac D & Kapoula Z. Latency of saccades and vergence eye movements in dyslexic children. Exp Brain Res 2008; 188: 1-12.
14. Pavlidis GT. Eye movement differences between dyslexics, normal, and retarded readers while sequentially fixating digits. Am J Optom Physiol Opt 1985; 62: 820-832.
15. Olson RK, Kliegl R & Davidson BJ. Dyslexic and normal readers' eye movements. J Exp Psychol Hum Percept Perform 1983; 9: 816-825.
16. Stanley G, Smith GA & Howell EA. Eye-movements and sequential tracking in dyslexic and control children. Br J Psychol 1983; 74: 181-187.
17. Brown B, Haegerstrom-Portnoy G, Adams AJ, et al. Predictive eye movements do not discriminate between dyslexic and control children. Neuropsychologia 1983; 21: 121-128.
18. Kuperman V, Van Dyke JA & Henry R. Eye-Movement Control in RAN and Reading. Sci Stud Read 2016; 20: 173-188.
19. Kiely PM, Crewther SG & Crewther DP. Is there an association between functional vision and learning to read? Clin Exp Optom 2001; 84: 346-353.
20. Taylor SE. Eye Movements in Reading: Facts and Fallacies. Am Educ Res J 1965; 2: 187-202.
21. Huestegge L, Radach R, Corbic D & Huestegge SM. Oculomotor and linguistic determinants of reading development: A longitudinal study. Vision Res 2009; 49: 2948-2959.
22. Grisham D, Powers M & Riles P. Visual skills of poor readers in high school. Optometry 2007; 78: 542-549.

23. Orlansky G, Wilmer J, Taub MB, et al. Astigmatism and Early Academic Readiness in Preschool Children. Optom Vis Sci 2015; 92: 279-285.
24. Scheiman MM & Wick B. Eye Movement Disorders. In: Clinical Management of Binocular Vision Heterophoric, Accommodative and Eye Movement disorders, 3rd edition, Lippincott Williams & Wilkins: Philadelphia, 2008; pp. 382-405.
25. Barrett BT. A critical evaluation of the evidence supporting the practice of behavioural vision therapy. Ophthalmic Physiol Opt 2009; 29: 4-25.
26. Fioravanti F, Inchingolo P, Pensiero S & Spanio M. Saccadic eye movement conjugation in children. Vision Res 1995; 35: 3217-3228.
27. Salman MS, Sharpe JA, Eizenman M, et al. Saccades in children. Vision Res 2006; 46: 1432-1439.
28. Pensiero S, Fabbro F, Michieletto P, Accardo A & Brambilla P. Saccadic characteristics in autistic children. Funct Neurol 2009; 24: 153-158.
29. Schmitt LM, Cook EH, Sweeney JA & Mosconi MW. Saccadic eye movement abnormalities in autism spectrum disorder indicate dysfunctions in cerebellum and brainstem. Mol Autism 2014; 5: 47, doi: 11.1186/2040-2392-5-47.
30. Rommelse NN, Van der Stigchel S & Sergeant JA. A review on eye movement studies in childhood and adolescent psychiatry. Brain Cogn 2008; 68: 391-414.
31. Ygge JN, Aring EVA, Han Y, Bolzani R & Hellstrom A. Fixation Stability in Normal Children. Ann NY Acad Sci 2005; 1039: 480-483.
32. Larsen DA & Bek T. The frequency of small saccades during fixation is age independent in children between 5 and 16 years of age. Acta Ophthalmol 2017; 95: 79-84.
33. Tiadi A, Gerard CL, Peyre H, Bui-Quoc E & Bucci MP. Immaturity of Visual Fixations in Dyslexic Children. Front Hum Neurosci 2016; 10: 58, doi:10.3389/fnhum.2016.00058.
34. Jones D, Westall C, Averbeck K & Abdolell M. Visual acuity assessment: a comparison of two tests for measuring children's vision. Ophthalmic Physiol Opt 2003; 23: 541-546.
35. Scheiman M, Gallaway M, Frantz KA, et al. Nearpoint of convergence: test procedure, target selection, and normative data. Optom Vis Sci 2003; 80: 214-225.
36. Saunders KJ, Woodhouse JM & Westall CA. The modified frisby stereotest. J Pediatr Ophthalmol Strabismus 1996; 33: 323-327.
37. Adler P, Scally AJ & Barrett BT. Test-retest reproducibility of accommodation measurements gathered in an unselected sample of UK primary school children. Br J Ophthalmol 2013; 97: 592-597.
38. McClelland JF & Saunders KJ. Accommodative lag using dynamic retinoscopy: age norms for school-age children. Optom Vis Sci 2004; 81: 929-933.
39. Tobii Technology AB. Product Description for Tobii TX300 Eye Tracker 2010, http://www.tobiipro.com/siteassets/tobii-pro/product-descriptions/tobii-pro-tx300-product-description.pdf, accessed 26/11/2014.
40. Fellows BJ. Chance stimulus sequences for discrimination tasks. Psychol Bull 1967; 67: 87-92.
41. Behrens F & Weiss LR. An algorithm separating saccadic from nonsaccadic eye movements automatically by use of the acceleration signal. Vision Res 1992; 32: 889-893.
42. Behrens F, Mackeben M & Schroder-Preikschat W. An improved algorithm for automatic detection of saccades in eye movement data and for calculating saccade parameters. Behav Res Methods 2010; 42: 701-708.

43. Boghen D, Troost BT, Daroff RB, Dell'Osso LF & Birkett JE. Velocity characteristics of normal human saccades. Invest Ophthalmol 1974; 13: 619-623.
44. Bahill A. The main sequence, a tool for studying human eye movements. Math Biosci 1975; 24: 191-204.
45. Garbutt S, Harwood MR & Harris CM. Comparison of the main sequence of reflexive saccades and the quick phases of optokinetic nystagmus. Br J Ophthalmol 2001; 85: 1477-1483.
46. Harwood MR, Mezey LE & Harris CM. The spectral main sequence of human saccades. J Neurosci 1999; 19: 9098-9106.
47. Ludbrook J. Multiple comparison procedures updated. Clin Exp Pharmacol Physiol 1998; 25: 1032-1037.
48. Ashby J, Rayner K & Clifton C. Eye movements of highly skilled and average readers: differential effects of frequency and predictability. Q J Exp Psychol-A 2005; 58: 1065-1086.
49. Juhasz B & Pollatsek A. Lexical influences on eye movements in reading. In: The Oxford handbook of eye movements (Liversedge S, Gilchrist I & Everling S, editors) Oxford University Press Inc: New York, 2011; pp. 873-893.
50. Callu D, Giannopulu I, Escolano S, et al. Smooth pursuit eye movements are associated with phonological awareness in preschool children. Brain Cogn 2005; 58: 217-225.
51. Quaid P & Simpson T. Association between reading speed, cycloplegic refractive error, and oculomotor function in reading disabled children versus controls. Graefes Arch Clin Exp Ophthalmol 2013; 251: 169-187.
52. Rosner J & Rosner J. The relationship between moderate hyperopia and academic achievement: how much plus is enough? J Am Optom Assoc 1997; 68: 648-650.
53. Creavin AL, Lingam R, Northstone K & Williams C. Ophthalmic abnormalities in children with developmental coordination disorder. Dev Med Child Neurol 2014; 56: 164-170.
54. Monger L, Wilkins A & Allen P. Identifying visual stress during a routine eye examination. J Optom 2015; 8: 140-145.

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 delayed reading	Mean ±SD	0.02 ±0.08	0.02 ±0.06	0.01 ±0.06	0.01 ±0.04	0.67 ±0.95	0.71 ±1.09
Children with delayed reading	Mean ±SD	0.04 ±0.08	0.02 ±0.08	0.00 ±0.06	0.00 ±0.04	0.58 ±0.66	0.54 ±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

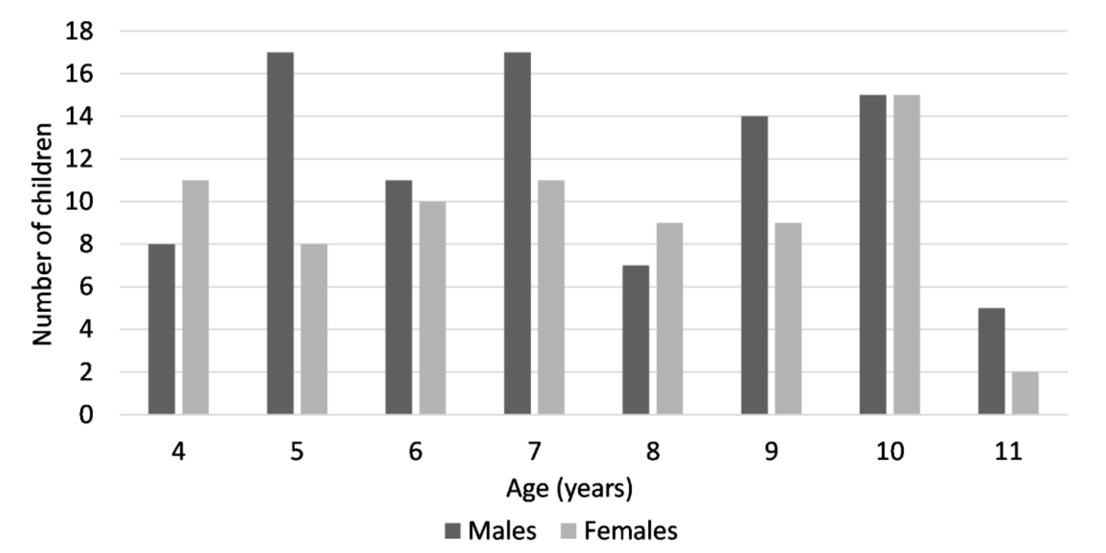

Figure 1. Histogram showing the age and gender distribution of the participants.

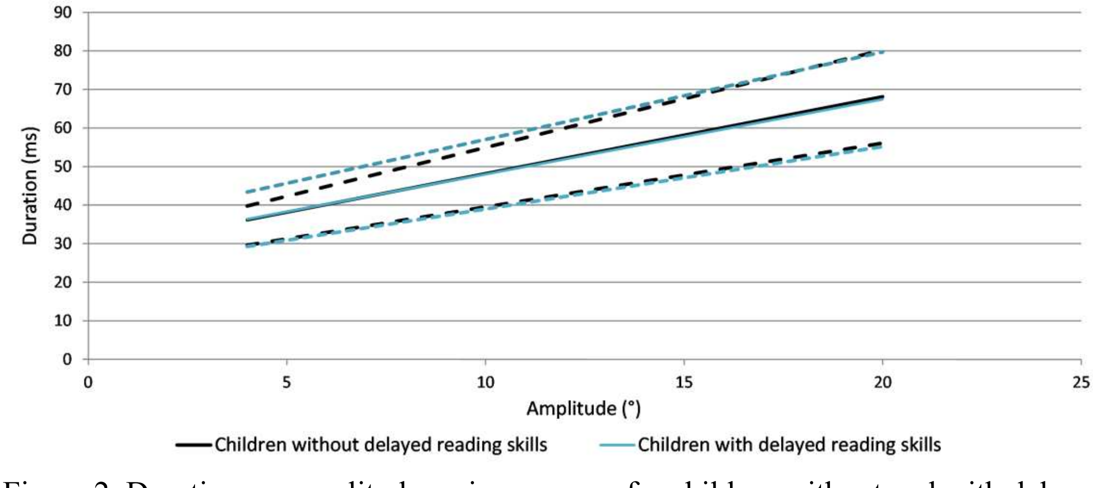

Figure 2. Duration vs. amplitude main sequence for children without and with delayed reading. The dashed line represents the mean duration vs. amplitude main sequence and the continuous lines represent ±SD for each group.

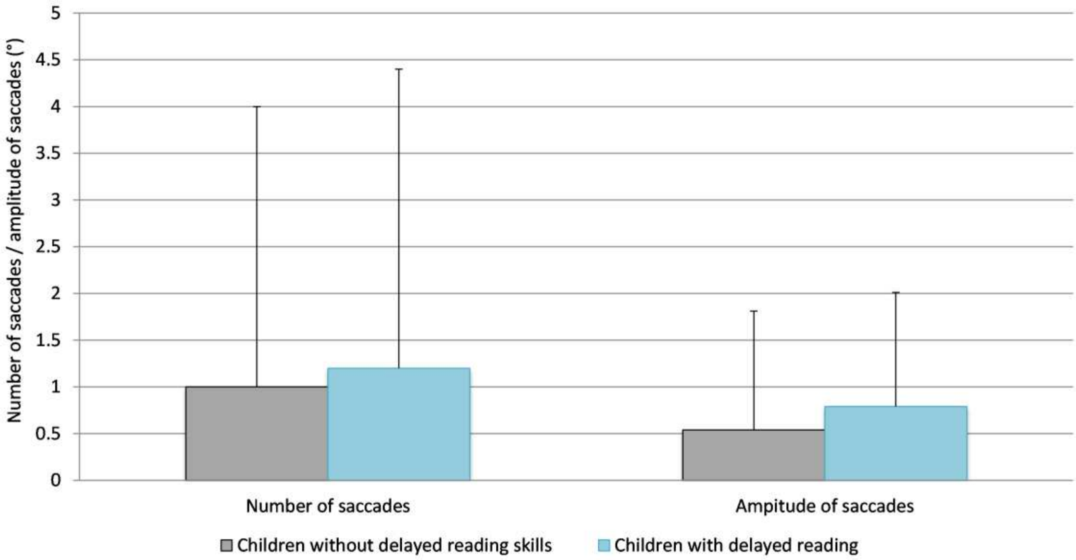

Figure 3. Fixation stability parameters for children without and with delayed reading skills. Values are medians for all participants in each group and the error bars represent the upper quartile (75th percentile).