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Using eye movements to predict reading skills in children

An eye tracking study while reading aloud a narrative

Thesis

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Content

Abstract

Learning to read is one of the most important competence that children acquire in primary school. Recent technological innovations have allowed us to study the relation between children's reading behaviour and their eye movements. The eye tracking method is expected to provide a more detailed insight on reading development than current reading tests. In the present study, we collected eye movements of a small sample of primary school children. Since eye tracking studies require reading from a monitor, we aimed first to establish that reading achievement from paper is similar to reading achievement from a monitor. We then explored which eye movement measures are good indicators for reading comprehension and reading achievement. Furthermore, we explored whether there are differences in eye movements between strong readers and weak readers and high comprehension level and low comprehension level. Finally, we compared reading achievement and eye movement measures between narratives of different reading level.

Twenty-two participants were offered 3 standardized narratives of different reading level. Eye movements from both eyes were recorded with an 60 Hz infrared eye tracker while the participants were reading aloud standardized narratives. Immediately after reading, participants had to recall the narrative and comprehension was scored by the experimenter. Reading achievement was calculated with reading speed and accuracy. Eye movement measures, re-reading time and total fixation duration were calculated using a saccade velocity threshold of 10 degrees per second and used to predict reading skills using a logistic regression approach.

Our first finding confirmed that there was no difference in reading speed when reading from paper and from a monitor (T = 1.69, $p = .09$). Participants did not show a pattern of re-reading sentences and therefore re-reading time could not be calculated. Moreover, we did not observe an effect of total fixation duration on reading comprehension ($\chi2$ (2) = .054, $p = .72$). We did observe an effect of total fixation duration on reading achievement ($\chi2$ (2) = 6.775 $p = .009$). Furthermore, we found that strong readers fixated less (U = 16, $p = .03$) and made less saccades (U = 13.5, $p = .013$) than weak readers. Likewise, strong readers had a shorter total fixation duration (U = 12, $p = .011$). Moreover, we found that participants made more fixations ($T = 97$, $p = .005$), saccades ($T = 86$, $p = .03$) and regressions ($T = 80.5$, $p = .01$) and had a higher total fixation duration ($T = 97$, $p = .04$) when reading a difficult reading level narrative compared to reading an age-appropriate reading level narrative.

We conclude that eye tracking has the potential to teach us on reading development in children. However, more studies are needed before eye tracking has enough reliability and validity to be used as an instrument for measuring reading skills.

Introduction

Normal reading achievement is a prerequisite for developing literacy skills and is necessary for academic performance (Radach & Kennedy, 2013). Reading disabilities interfere with academic performance and the development of cognitive functions (Viljaranta et al., 2016). Likewise, reading disabilities might lead to motivational problems and a low self-esteem. Due to the reading disabilities. Children often have less frequent exposure to difficult texts, which further exacerbates their reading disabilities (Vorstius, Radach & Lonigan, 2015). In order to offer early intervention for these children, early detection of reading disabilities is important.

Learning to read requires two strategies. The first reading skill involves the ability to translate graphemes into phonemes, which is referred to as phonologic recoding and demands cognitive resources to pronunciation that therefore cannot be allocated to comprehension (Cunningham & Stanovich, 1997). The second reading skill is visually based retrieval, which involves the ability to process a word's meaning from its visual form (Bradley & Bryant, 1985). Readers using this skill have more cognitive resources left for comprehension (Viljaranta et al., 2016). This skill however requires the child to have a wide vocabulary and mental representations of words (Tiffin-Richards & Schroeder, 2015). A common assumption is that a child should have well enough reading skills before comprehension can be utilised (Kaakiken, Lehtola & Paattilammi, 2015).

When learning to read fails, early detection of reading disabilities is important. Reading achievement in the Netherlands is determined by the teacher who measures time and accuracy while a child reads aloud standardized narratives from paper. Children pass the test when they read fast. Criticism on this method is characterized by the focus on the reading speed, causing children to rush when reading and less focus on comprehension and comprehension. Additional measurement with eye tracking might be an objective method to learn more about children's reading development and inform us which factors interfere with reading skills and which interventions are beneficial. Today's eye tracking is conducted with non-invasive infrared video-based eye monitors and requires only limited effort from a child.

Recent technological innovations in eye tracking have allowed researchers to investigate the relation between reading behaviour and eye movements (Starr & Rayner, 2001), as it has been argued that an inadequate development of eye movement control might cause reading disabilities (Schotter, Tran & Rayner, 2014). Previous findings, as described in Foster, Ardoin & Binder (2015) and Huestegge, Radach, Corbic & Huestegge (2009), suggest that measuring eye movements has the potential to offer valuable information regarding reading achievement. Eye movement data could be beneficial for teachers in objectively predicting reading achievement and diagnosing reading disabilities at an early stage that in turn could inform teachers on early intervention and educational reading instructions. However, current eye tracking studies primarily focus on effects of experimentally manipulated text characteristics (van der Schoot, Vasbinder, Horsley & Lieshout, 2008; Kaakiken, Lethtola & Paattilammi, 2015; Schotter, Tran & Rayner, 2014), but very few studies have investigated the relation between eye movements and reading achievement in general.

In most adult eye tracking studies, eye movements are characterized by fixations, saccades and regressions as described by Rayner (1978). Saccades are a rapid, jerky type of eye movement separated by fixations. We move our eyes in order to relocate the fovea—that part of the retina where we see most sharp—over the text we wish to process. Between the saccades, the eye is relatively still in a fixation. Visual input is processed during this fixation. A regression is a reversed movement in opposite reading direction. Regressions occur in order to re-read text. Relatively little research has been conducted to study eye movements in children. However, early eye tracking studies indicate that eye movements in young readers are quite different from those of skilled readers (Rayner, 2001; Blythe & Joseph, 2011). Developing readers typically make more fixations (Tiffin-Richards & Schroeder, 2015), have longer fixation duration (Vorstius, Radach & Lonigan, 2015), make shorter saccades (Salman et al, 2006), and have more regressions (Starr & Rayner, 2001) compared to skilled readers. Likewise, difficult sentences lead to longer fixations, shorter saccades and more regressions (Foster, 2017). These findings have been observed very consistently as summarised in Schroeder, Hyona and Liversedge (2015).

Three common used measures (Cunnings, Patteron & Felser, 2014) in eye tracking studies are based on fixation duration. 1) The first-pass reading time, represents the sum of all fixation durations on a sentence during its first inspection, which is before the eyes make a saccade past the sentence. 2) The re-reading time is the sum of all fixation durations on a sentence after the eyes made a saccade past the sentence. According to Vorstius, Radach & Lonigan (2015) re-reading time reflects later stages of higher processing such as comprehension. Suggesting that reading a text with the intention of comprehension will result in a relatively high re-reading time, which has been found by Kaakiken, Lehtola & Paattilammi, 2015) and increased re-inspections of the sentence (van der Schoot, Vasbinder, Horsley & van Lieshout, 2008). According to Schotter, Train & Rayner (2014) an increase in regressions suggest that higher-level linguistic processing causes the reader to reread text in order to correct a failure in comprehension of the sentence. 3) The total fixation duration is the sum of all fixation durations on a sentence. Total fixation duration includes first-pass reading time and re-reading time and therefore reflects low-level and high-level processing (Foster, Ardoin & Binder, 2017; Radach & Kennedy, 2013).

In the present study, we used eye tracking to study the relation between children's eye movements and reading skills. Since eye tracking requires reading from a monitor, the first aim in this study was to establish that reading achievement measured with standardized narratives was the same from paper as from an eye tracker monitor. We then aimed to examine the effect of eye movements on reading comprehension and reading achievement. We expect that re-reading time and total fixation duration predict reading achievement and reading comprehension. Furthermore, we explored which eye movements can differentiate between strong and weak readers. We expect a different eye movement pattern in children with high reading achievement. Finally, we were interested which eye movements differ when reading a difficult narrative compared to an age-appropriate reading level narrative. We expect that a difficult narrative leads to a different eye movement pattern.

Methods

Design

This study was a 3*2 factorial design within-subject design. Three narratives on varied reading difficulty level were offered in two conditions: on paper and on a computer monitor. Reading condition and the order of narratives were randomized. Independent interval eye movement variables were number of fixations, saccades and regressions, re-reading time, total reading time. Other independent interval variables were reading speed and number of misread words. Outcome categorical variables were reading comprehension and reading achievement.

This study was part of a larger study on the implementation of the eye tracker in the visual rehabilitation centre Koninklijke Visio, Rotterdam in cooperation with the department neurosciences of Erasmus University Medical Centre, Rotterdam, (protocol number 60-00635-98-110). Experimental procedures were approved by the Medical Ethical Committee of Erasmus University Medical Centre, Rotterdam, The Netherlands. The study adhered to the Declaration of Helsinki for research involving human subjects.

Participants

A small sample of school-aged children was recruited from a primary school in the Rotterdam area in The Netherlands. In total 22 children enrolled in the study; 16 male, 6 female, mean age 8.5 years, age range: 7-10.5 years. Inclusion criteria was normal or corrected to normal visual acuity. Exclusion criteria were wearing glasses with high power (≥+6D and ≤-6D) because of problems with the calibration procedure on the eye tracker. This information was gathered from the teacher who completed a questionnaire. Information on medical history, family race/ethnicity and socioeconomic status was not available for this sample. Parents were informed about the purpose of this study by letter and an additional information folder before signing the consent. Parents and teachers were informed by letter on the general conclusion of the study. Participants received a certificate for their participation in the experiment.

Materials

Three narratives were adopted from the Analyse van Individualiseringsnormen (AVI), an educational measurement for reading achievement that is used in primary school in the Netherlands (Struiksma & van der Leij, 2009). The AVI offers short narratives on nine reading levels. AVI has an updated version since 2008, with new narratives and new standardization (Struiksma, van der Leij & Vieijra, 2012). For this study, we have used the older version of the AVI, so that we would not interfere with educational measurements at the school. This older version is still used for children who need testing more than once. For this study, two age-appropriate AVI4 reading level narratives and one relatively difficult AVI6 reading level narrative were selected. Analysed sentences consisted of 6-9 words and had a mean length of 34 letters (*SD* = 2.8).

Apparatus

In the paper condition, the narrative was presented in Verdana font 10pt, left aligned with 1.5 line spacing in black and white and was placed on a reading stand. Viewing distance was 32 cm. The experiment leader recorded reading time and with a stopwatch and wrote down misread words and spoken responses. In the monitor condition, narratives were presented in Verdana font 20pt, left aligned with 1.5 line spacing in black and white on a grey background using a 24 inch monitor. Viewing distance was 65 cm. Eye movements from both eyes were recorded with an infrared eye tracker (Tobii T60XL, Tobii Corporation, Sweden) using a 60 Hz sampling rate. A five point calibration procedure was performed at the beginning of each narrative to determine accurate gaze point data. Each participant was taped on video using an integrated webcam. All measurements were stored on the hard disk and not connected to the internet.

Procedure

Participants sat in an unused classroom in their school and were informed about the purpose of this study. Participants were asked to read three narratives aloud as fast and as accurate they could. They were offered two narratives on their estimated current reading level and one difficult narrative. Participants were told that when they would make an error, they would only have to re-read the mistaken word and not the entire sentence. To ensure that participants were reading for comprehension, participants were told that they had to recount the story and that they would be asked questions about the story. At the end of each narrative, participants were asked to recall events in the narratives. The total duration of the experiment was approximately 20 minutes per participant.

Eye movement analysis

Eye movement data of one sentence from each narrative was manually analysed using MATLAB 7.11.0. The analysed sentences are presented in the appendix. The appendix also shows an example of eye movement data from a participant in this study. Eye movement data was first inspected visually to detect any possible problems before it was analysed. Six participants who showed small eye movements such as tremors, drifts and flicks resulting in unstable fixations or track loss were excluded from analysis. Based on visual inspection of the eye movement data, fixations and saccades were identified using a fixed saccade velocity threshold of 10 degrees per second. Each eye location point was classified as a fixation when velocity was below this threshold otherwise it was identified as a saccade. This identification method is described by Salvucci & Goldberg (2000). Three standard eye movement measures were calculated, including first-pass reading time (all fixations before a saccade past the sentence was made), re-reading time (all fixations after a saccade past the sentence was made) and total fixation duration (all fixations). Number of fixations, saccades and regressions were counted.

Outcome variables

Outcome variables were reading comprehension and reading achievement. Spoken responses were scored during testing by the experimenter. Participants were divided by comprehension score. Participants could earn one or zero points for comprehension. One point was rewarded if participants could give correct free-recall details about the narrative, zero points were given if the response was incorrect or if the participant responded, “I don’t know”. Two groups were created: participants were classified strong or weak readers according to norm scores of the AVI test. Participants reading the narratives under 105 seconds with a maximum of 5 misread words were labelled strong readers, otherwise participants were labelled weak readers. Words were counted as misread when they were mispronounced, skipped, or switched. Adding a word was also counted as a misread word.

Statistical analyses

The data analyses were carried out using SPSS 24. Significance level was set at .05.

To compare reading achievement from paper with reading achievement from a monitor, we used a non-parametric Wilcoxon Signed Rank Test, since data were not normally distributed. To predict reading comprehension and achievement, we were interested in the influence of re-reading time and total fixation duration. However, since participants did not show a pattern of re-reading sentences, we only used total fixation duration as a regressor. To predict reading comprehension, total fixation duration was analysed with a logistic regression model. A Bonferroni correction was applied using both terms in the model resulting in statistical significance being accepted when $p < .025$ (Tabachnick & Fidell, 2007). Furthermore, the number of fixations, saccades and regressions and total fixation duration were compared by comprehension score, using a Mann-Whitney U Test. To predict reading achievement, total fixation duration was analysed with a logistic regression model. A Bonferroni correction was applied using both terms in the model resulting in statistical significance being accepted when $p < .025$ (Tabachnick & Fidell, 2007). Furthermore, the number of fixations, saccades and regressions and total fixation duration were compared by reading achievement, using a Mann-Whitney U Test. To compare reading achievement on a difficult narrative and a narrative on current reading level, we used a non-parametric Wilcoxon Signed Rank Test, since data were not normally distributed.

Results

Participant characteristics

Two children had a presumption of dyslexia, but this did not interfere with the procedure so participants were kept in analysis. Of the 22 participants, 13 were classified as strong readers and 9 were classified as weak readers; 17 scored 1 point for comprehension and 5 scored 0 points for comprehension.

1. **Comparing reading from paper with reading from a monitor**

Table 1 presents descriptive statistics of the AVI4 narratives sorted by reading condition. We found no difference between reading speed from paper and reading speed from a monitor and no difference between the number of misread words from paper and number of misread words from a monitor.

Table 1

Descriptive statistics of the reading conditions

	Paper	Monitor	sig. *z*
Mean reading speed	90.7 (*44.6*)	96.6 (*46.3*)	*ns*
Misread words	0-14	0-19	*ns*

We found no difference between reading speed from paper and reading speed from a monitor ($z = 1.69$, $p = .09$), and no difference between the number of misread words from paper and number of misread words from a monitor ($z = 0.79$, $p = .43$).

2. **Predicting reading comprehension**

We then analysed the effect of eye movements on reading comprehension. Participants were divided by reading comprehension: high ($n = 14$) or low ($n = 4$).

To predict high or low comprehension, we were interested in the influence of total fixation duration. A logistic regression was performed to analyse the effect of total fixation duration on reading comprehension. The logit of re-reading time and total fixation duration was found to be linearly related to comprehension via the Box-Tidwell (1962) procedure. P? The logistic regression model was not significant; therefore, we found no effect of total fixation duration on comprehension ($\chi2$ (2) = .054, $p = .72$).

We compared the number of fixations, regressions and saccades and total fixation duration between high and low comprehension. We found no difference in the number of fixations (U = 32.5, $p = .81$), saccades (U = 28.5, $p = .89$) and regressions (U = 32, $p = .89$) and total fixation duration (U = 27, $p = .810$) between high comprehension and low comprehension.

3. **Predicting reading achievement**

We then analysed the effect of eye movements on reading achievement. Participants were divided by reading achievement; strong (*n* = 11) or weak (*n* = 7).

To predict strong or weak reading achievement, we were interested in the influence of total fixation duration. A logistic regression was performed to analyse the effect of total fixation duration on reading achievement. The logit of re-reading time and total fixation duration was found to be linearly related to reading achievement via the Box-Tidwell (1962) procedure. The logistic regression model was significant ($\chi 2$ (2) = 6.775 p = .009). The model explained 51.1% (Nagelkerke R2) of the variance in reading achievement and correctly distinguished between strong and weak readers 87.5% of cases.

Furthermore, we compared the number of fixations, regressions and saccades and total fixation duration between strong and weak readers. Table 2 shows eye movement data of strong and weak readers. Strong readers fixated less than weak readers and fixated shorter than weak readers. Strong readers made less saccades than weak readers. We found no difference in number of regressions between strong and weak readers.

Table 2. *Eye movement data of strong and weak readers*

	Strong readers *N* = 11		Weak readers *N* = 7		U	*p*-value
	M	*SD*	M	*SD*		
Fixations	8	3.6	13	5	16	.03
Saccades	5	3	9	4	13.5	.01
Regressions	1	1	1	2	31.5	.38
Total fixation duration (ms)	158	527	3183	1208	12	.01

4. Comparing reading level

18 of 22 participants read the difficult AVI6 narrative. Eye movement data of 15 participants was further analysed. Three participants were excluded from further analysis due to spurious fixations.

We compared the number of fixations, regressions, saccades and total fixation duration between the difficult narrative and age-appropriate reading level narrative. Table 3 shows eye movement data of the analysed AVI4 and AVI6 sentence. Participants made more fixations and fixated longer on the AVI6 sentence. Furthermore, participants made more saccades and regressions in the AVI6 sentence compared to the AVI4 sentence.

Table 3. *Eye movement data of the AVI4 and AVI 6 sentence*

	AVI 4; *N*=18		AVI 6; *N*=15		T	*p*-value
	M	*SD*	M	*SD*		
Fixations	10	5	14	6	97	.005
Saccades	7	4	9	4	86	.03
Regressions	1	1	3	3	80.5	.01
Total fixation duration (ms)	2116	1123	2450	1209	97	.04
Total reading time (ms)	2811	1328	3495	1460		

Discussion

Recent technological innovations in eye tracking have allowed elaborative studies on eye movements in children. However, little is still known about children's eye movement behaviour in relation to reading behaviour. In the present eye tracking study, we collected eye movements of school-aged children while reading a coherent narrative and used the eye movement data to study the effect of eye movements on reading comprehension and reading achievement. We found that total fixation duration, number of fixations and saccades have an effect on reading achievement. Furthermore, we found that eye movement behaviour differs between narratives of different reading level.

Since eye tracking studies require reading from a monitor, the first aim of the present study was to compare reading achievement in children while reading from paper and reading from a monitor. As hypothesized, we found no difference between reading speed and reading accuracy between reading conditions. Our finding support the premise that studying reading behaviour from a monitor is representative for natural reading from paper.

The second aim of this study was to explore which eye movement measures are predictors for reading comprehension. We were interested in re-reading time and total fixation duration. These eye movement measures are interpreted as being reflective of cognitive processes that underlie reading comprehension (van der Schoot and others, 2008). We hypothesized that high re-reading time could predict reading comprehension. However, in this study participants did not re-read prior sentences, therefore we could not use re-reading time as an independent variable for reading comprehension. We then explored the relation between total fixation duration and reading comprehension in a logistic regression analysis and found no relation. Furthermore, we found no difference between readers with high and low comprehension in the number of fixations, saccades and regressions they made.

This finding is in contrast with previous research such as Vorstius, Radach & Lonigan (2015) which showed that total fixation duration was associated with higher cognitive processes. Our finding also contradicts with van der Schoot and others (2008) who found that readers with good comprehension skills reread specific informative parts of texts. One hypothetical explanation for not re-reading sentences in this study is that the selected narratives were too simple for our study purposes and that perhaps longer and more difficult sentences would have provoked re-reading. Another explanation, continuous sentences might would have provoked actual re-reading, however in this study each sentence was presented on a separate line. A third explanation, only eye movements on the analysed sentence were captured. It might be possible that participants showed vertical movements that we did not capture.

The third aim of this study was to explore which eye movement measures are predictors for reading achievement. We hypothesized that total fixation duration predicts reading achievement. We found that total fixation duration did explain a significant amount of additional variance in reading achievement. From this finding it may be inferred, that eye movements of one sentence can predict such a complex task like reading achievement. Accordingly, we found that weak readers made more fixations, saccades and regressions compared to strong readers. Suggesting that strong readers show more control of their eye movements than weak readers. This finding has been described in other eye tracking studies in children (Schroeder, Hyona & Liversedge, 2015).

The fourth aim of this study was to explore which eye movement measures differ between narratives of a different reading level. We expected a different eye movement pattern when a participant reads a difficult narrative compared to an age-appropriate narrative. We found that reading speed on the difficult narrative was longer compared to reading speed on the age-appropriate narrative. Furthermore, participants made more fixations, regressions and saccades and had a higher total fixation duration.

Our results should be interpreted with consideration of the following limitations. First, due to the low refresh rate we could not accurately calculate a saccade velocity threshold. Also, there is still a lack of research on the saccade velocity threshold in school-aged children. It is expected that children make less acceleration when they move their eyes to a next target compared to adults. Therefore the saccade threshold that is being used in adults is not acceptable in children. The saccade velocity threshold in adults lies between 20 and 30 degrees per seconds (Salvucci & Goldberg, 2000). After a visual inspection of a sample of sentences in our study, our threshold was set 10 degrees per second. This may have led to too little or too much identification of saccades and fixations. Another limitation in identifying saccades and fixations is that children more often make small eye movements such as tremors, drifts and flicks than adults do. Furthermore, it should be taken into account, that the sample size was relatively low for analyses. Also, it should be noted that the level of comprehension and achievement were not equally divided. These limitations could be improved by increasing the number of participants who are offered a more challenging narrative and we suggest eye movement data should be analysed with an accurate saccade velocity threshold.

Using the eye tracking method in children is a new field of research in which we explored which eye movements children make during an oral reading task. We tried to mimic natural reading aloud a coherent narrative as in educational practices and we tried to predict reading skills. Taken together, we confirmed that there is a relation between children’s eye movements and their reading skills. An important conclusion of the present study is that more eye tracking research on reading development is worthwhile. More studies are needed before eye tracking studies have enough reliability and validity to inform teachers on educational practices. Our results yield for further eye tracking research in order to gain a full understanding of the interplay between eye movements and general reading development. We believe eye tracking has the potential to inform teachers on why a child has difficulty learning to read and to test whether an reading intervention has led to an actual change in a child’s reading behaviour, since the currently used reading test may be insufficient sensitive to uncover these changes.

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Appendix

Table A1

English translation of analysed sentences

Dutch sentence	English sentence
4A: Boven in de toren hangt een lange buis.	At the top of the tower hangs a long tube.
4B: Gaan jullie mee fietsen? vraagt Joep.	Are you coming along to cycle? Joep asks.
6: Daar kun je opeens veranderen in een oude man.	There you can suddenly change into an old man.