frontiers | Frontiers in Education

TYPE Original Research
PUBLISHED 25 July 2023
DOI 10.3389/feduc.2023.1077882

OPEN ACCESS

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RECEIVED 17 November 2022
ACCEPTED 28 June 2023
PUBLISHED 25 July 2023

CITATION
Strandberg A, Nilsson M, Östberg P and Seimyr GÖ (2023) Eye movements are stable predictors of word reading ability in young readers.
Front. Educ. 8:1077882.
doi: 10.3389/feduc.2023.1077882

Eye movements are stable predictors of word reading ability in young readers

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During the first years of formal instruction in reading, there are developmental changes to the characteristics of children's eye movements that correspond to their progress. Generally, these changes are driven by improved text processing and a shift from reliance on sub-lexical to lexical processes. Currently, however, little is known about to what extent early eye movements during reading in ecological contexts account for variations in later word reading ability. In this paper we investigate this association in 164 children in first grade and 206 children in second grade. We recorded their eye movements during normal text passage reading in an unrestricted eye tracking set-up. We analyzed to what extent they account for variation in word reading ability 1year post-recording, and make comparisons to concurrent predictions. Regression analysis revealed that eye movements accounted for approximately 60% of the variance in concurrent word reading ability and approximately 48% 1year later. Mean fixation duration explained unique variance in reading ability and largely drives the correlation. Proportion of regressions was not a significant longitudinal predictor among the youngest readers. The difference between the concurrent and longitudinal predictions was greatest in the younger children, which was in line with our expectation. Findings are discussed in relation to current models of word reading. Our results suggest that eye movements are stable predictors of word reading ability. Ultimately, knowledge of what can be gleaned from early readers' natural eye movements about later word reading ability could help inform assessments of reading development in the educational setting, where the presence of digital assessment tools is growing.

KEYWORDS
eye movements, text reading, eye tracking, reading development, word reading ability

1. Introduction

Eye tracking is used to study a variety of topics within several areas of research, such as medicine, education and psychology (Henderson et al., 2015; Mcdonald et al., 2015; Ekstrand et al., 2021). Its' temporal and spatial sensitivity makes it particularly suitable for investigations into the reading process (Carter and Luke, 2020). Indeed, eye movement research has taught us a great deal about the psychological, neurological and linguistic aspects of adult reading (Rayner and McConkie, 1976; Gidlöf et al., 2013; König, 2016; Zhang et al., 2021) while children's reading development long was sparsely studied. As there are differences to the mechanics of text processing depending on proficiency, the findings from adult studies are not always applicable

10.3389/feduc.2023.1077882

to young readers (Rayner, 1998; Reichle et al., 2013). However, reading is widely considered an indispensable skill and one of the most cognitively demanding tasks that we engage in on a daily basis. The first school years are critical to its' acquirement, which makes children's reading development an area of continued interest.

1.1. Adults' eye movements during reading

A great deal of eye movement research has contributed to our understanding of the reading process in skilled, mostly adult, readers (Rayner, 1975, 1998; Rayner and McConkie, 1976; Inhoff, 1990). Development of innovative experimental techniques has allowed researchers to investigate word processing and moment-to-moment allocation of attention while the individual reads a text (McConkie and Rayner, 1975; Rayner, 1975; Clifton et al., 2016). Throughout all orthographies studied to this date, adult's eye movements consistently follow a fixation-saccade pattern during reading. This means that when we read, our eyes make a series of stops and between those stops, horizontal movements from left to right across the text (in alphabetic writing systems). Those stops and fast gaze movements are what are referred to as fixations and saccades. During a fixation, the reader holds their gaze still over a word before moving, i.e., making a saccade, onto the next. A number of different variables, all tied to these aspects of online text processing, are analyzed within this field. These are either of spatial (e.g., the distance the eyes move during a saccade), numerical (e.g., the number or proportion of regressions) or temporal nature (e.g., the duration of a fixation; Rayner, 1998). They may also move the gaze backwards, which is called a regressive saccade or regression. Variations in eye movement characteristics reflect the relative ease with which the reader progresses through the text (Rayner, 1977; Yang, 2012). In general, fluctuations in those variables are interpreted as indications of text processing difficulty rather than the cause thereof (Rayner, 1977; Just and Carpenter, 1980).

In adult readers, a fixation typically lasts between 60 and 500 ms (milliseconds) with an average of 250 ms (Rayner, 1998). Fixations are directly affected by the length and the frequency of the fixated, word as well as by lexical predictability. The longer the word, the higher is the probability that the reader refixates it and low-frequency words are fixated for a longer time than high-frequency words (Rayner and McConkie, 1976; Rayner and Duffy, 1986; Liversedge and Findlay, 2000; Joseph et al., 2013). Word frequency effects are really the effects of lexical processing, a necessary operation to access the word's meaning (Reichle et al., 2013). Repeated exposure to print strengthens the links between form and meaning in memory. Over time, word recognition requires shorter and fewer fixations. This process is widely considered an important driving force of eye movements during reading (Rayner and McConkie, 1976; Just and Carpenter 1980; Inhoff, 1984; Rayner, 1986; Rayner and Duffy, 1986; Clifton et al., 2007; Reichle et al., 2009; Rau et al., 2014; Blythe et al., 2015; Tiffin-Richards and Schroeder, 2015).

Rayner et al. (Reichle et al., 2009) describes an initial stage of processing taking place during fixations, where our decoding system quickly determines whether the word is likely to be identified. When a certain threshold is reached, a saccade to the next word is programmed. Following that, the second stage entails lexical access to the word. In parallel, the reader extracts relatively low-level visual and linguistic information, such as letter shape, word length and phonological cues, parafoveally to the right of the fixation. These estimations of the upcoming print help guide the eyes where to go next (Reichle et al., 1998; Rayner et al., 2004; Pollatsek et al., 2006). Saccades are affected by the processing difficulty experienced by the reader and struggling readers tend to make shorter saccades (Liversedge and Findlay, 2000; Hindmarsh et al., 2021). In English adults reading English text, a progressive saccade is approximately 7–9 letter spaces or 3–4 degrees in amplitude (Rayner, 1998; Liversedge and Findlay, 2000; Seassau and Bucci, 2013). Approximately 15–20% of all saccades are regressive, or regressions, which are associated to several functions. Regressions move the eye opposite of the reading direction, i.e., from right to left in alphabetic orthographies. They may resolve oculomotor targeting errors or let the reader review and reprocess a word with the purpose of validating or updating the reader's comprehension of the text (Inhoff et al., 2019). Adult studies have compellingly shown how cognitive processing is reflected in eye movements during reading. Research focusing on young individuals faces challenges relating to ethics, technology and the complex interplay of cognitive and visual processes during reading development. These factors have contributed to a gap in knowledge on how text processing and processing difficulties are represented in children's eye movements during reading. Nevertheless, progress has been made in the last decades, which we will turn to next.

1.2. Children's eye movements during reading

In the wake of important technical advancements, recent years have seen a growing body of eye tracking research on reading development (Sovik et al., 2000; Blythe et al., 2006, 2011, 2015; Häikiö et al., 2009; Joseph et al., 2013; Reichle et al., 2013; Blythe, 2014; Vorstius et al., 2014; Spichtig et al., 2016; Kornev et al., 2019) which have examined how progress is reflected in young readers' eye movements (Blythe, 2014). Young readers have a higher number of fixations and longer fixation durations than older, proficient readers. They make a higher number of short forward saccades and make regressive saccades more often than adults (Rayner, 1986; Inhoff et al., 2019). In general, regressions decrease in frequency as the child's reading improves and the occurrence of errors relating to both decoding and comprehension become rarer. Children's eye movements during reading largely resemble those of adults around 10–12 years of age (Rayner and Duffy, 1986; Blythe et al., 2009; Reichle et al., 2013; Blythe, 2014; Strandberg et al., 2022). Commonly, studies across age groups have informed researchers about this development (Blythe et al., 2009, 2011; Häikiö et al., 2009). Like adults', children's gaze durations are significantly longer for low than high-frequency words (Joseph et al., 2013). Word recognition processes involve a cognitive load which presumably is higher in beginning than skilled readers. This affects the preprocessing of upcoming letters and any other retrievable information from their perceptual span, which is smaller than that of adults (Rayner, 1986; Kim et al., 2019). Indeed, the gaze behavior of adult, struggling readers share several characteristics with that of very young readers (Prado et al., 2007; Barnes and Kim, 2016). Struggling readers tend to have longer fixations, a higher number of fixations and saccades, and make shorter forward saccades which is indicative of longer processing times (McConkie and Rayner, 1975; Rayner, 1998; Al Dahhan et al., 2014).

Hence, the number and duration of fixations decrease, refixations decrease, the number of saccades decreases while forward saccade amplitude increases, and the proportion of regressive saccades decrease over time despite increased text difficulty (Blythe, 2014; Strandberg et al., 2022). This account of young readers' eye movements is consistent with current developmental models of word reading (Blythe et al., 2011; Reichle et al., 2013; Blythe, 2014). Above, lexical processing is mentioned as a crucial route during reading. However, very young children largely depend on sub-lexical processes to decode text. Children initially learn how to read small units of print, while simultaneously trying to make the connections between orthography to phonology and semantics (Rau et al., 2014, 2015b). Over time, when the necessary links have been established, the quite demanding letter-by-letter processing that initiates reading acquisition gradually develops to automatized orthographic reading (LaBerge and Jay Samuels, 1974; Ehri, 2005, 2014).

The research that we have described here has developed our understanding of children's text processing and the knowledge that can be gained from their eye movements during reading. Some areas are still poorly understood, including what, if any, conclusions that can be drawn about future word reading ability based on early eye movements. We know that current reading skill is reflected in gaze patterns. However, it is unclear with what certainty we can estimate children's reading ability at a later point based on early reading eye movements.

1.3. Underpinnings of the present study

While the branch of reading research that focuses on text comprehension often deals with higher-level processes, the Lexical Quality Hypothesis developed by Perfetti and Hart (2001) emphasizes a lexical basis of comprehension. In this view, understanding of word meanings is central to global text comprehension. Perfetti (2010) describes a two-fold mechanism of progress; understanding a text lets children add specific semantic word knowledge to their vocabularies, while it also allows application of that new knowledge when reading other texts that contain those words. Several accounts of inter-reader differences focus on cognitive differences, which do not fully explain differences in knowledge of word meanings that remain throughout literacy development (Perfetti, 2010). Evidence that vocabulary training has effects on global comprehension (Beck et al., 1982) suggests that word knowledge should be taken into account when considering individual differences in reading. In this paper, we analyze a composition of tests that reflect fluency, accuracy and speed. Altogether, it is representative of abilities that support word level processes (Kamhi and Catts 2005). We assume word level processing to be a significant marker of reading ability and important for the continued reading development. While the assessment carried out highlights decoding and processing of words, rather than knowledge of words, there is arguably tight interplay between the skills during reading. We have chosen this stance based on a paradigm where word reading and comprehension are considered dissociated abilities, insofar that they are supported by partly different sets of underlying component skills. However, there is also an overlap between word level operations and text comprehension in developing readers (Hosp et al., 2019). In this study, we analyze word reading ability because smooth decoding is a crucial component of the reading process. It allows rapid word identification and retrieval of word meanings (Perfetti, 2010). We assume that it to some extent reflects abilities that assist text comprehension as well.

Assessments of reading ability within the educational setting are largely dependent on offline measures (Kim et al., 2019). It often demands some response on the student's behalf, be it verbal or written. Additionally, assessments are essentially always multipart. While they may give the instructor an idea of the students' reading ability, they are time consuming. According to Swedish Agency for Health Technology Assessment and Assessment of Social Services (SBU), more than 50 different tests are used to diagnose reading difficulties and none of them have been scientifically evaluated. On an international level, the report found scientific basis for very few assessments (Statens beredning för medicinsk utvärdering (SBU), 2014). Furthermore, nearly all screening protocols available require manual scoring and subjective assessment of the performance, which entails a risk of interrater variation. Finally, records show that the average age of diagnosis of reading difficulties in Sweden is 13 years, while early detection for reading difficulties is significant in terms of success of treatment (Denton et al., 2006; Zijlstra et al., 2021). Investigations of behavioral measures in this context have yielded some promising results. Eye movement patterns have been used to identify students with reading difficulties with high accuracy in a few studies (Rello and Ballesteros 2015; Ygge et al., 2016). The current study attempts to extend findings from this area to a diverse sample and a natural reading situation in a longitudinal design. Eye movement analysis could be used in the educational setting in the future, given a continued development of eye tracking technology toward accessibility and more manageable administration. It could potentially offer a fast analysis and an objective perspective in reading assessments in the academic or clinical setting. While most available offline tests of reading provide information about current reading ability, longitudinal coherence of the outcomes or predictive validity of the test materials is most often not evaluated. An ultimate goal for gaze behavior analysis could be to work as a complementary tool that provides quick and highly accurate predictions of word reading ability in young children (Rello and Ballesteros 2015; Ygge et al., 2016).

There is considerable variation to the methodological aspects of previous eye movement research on children's reading. Oftentimes, data is collected under controlled experimental conditions, most often in a research lab. Elements that minimize the influence of movements are common, such as head-tracking devices and chin- or head-rests. Other constraints concern how the stimuli are modeled and presented. Researchers can use gaze contingent techniques (such as the disappearing text or moving window paradigm; McConkie and Rayner, 1975, 1976) and present the participant with letters, words or sentences; one-by-one or sequentially. Restrained set-ups are associated to precise results and have contributed significant insight into the reading process. However, as is frequently the case where a phenomenon that naturally occurs in uncontrolled environments is studied in a controlled setting, the inherent characteristics of highly controlled set-ups may decrease the generalizability of findings. Their relevance for the educational setting, for example, where natural reading of print or on screens is practiced is theoretically somewhat limited. Unrestrained set-ups are associated with larger margins of error and more variability and are less common in this field of research. Hence, there is less knowledge about children's eye movements during reading in authentic contexts. Therefore, the participants of the current study read normal text passages at the location of their school to resemble a normal reading situation and to represent the probabilistic, uncertain nature of the everyday environment.

Reading ability is crucial throughout life, while its foundation is established during early childhood. Despite progress during recent years, investigations into children's reading continue to be of importance. So far, little research investigates children's eye movements and reading ability over time (Spichtig et al., 2016; Kim et al., 2019) within the same subjects. We know that gaze behavior during reading is a good real-time measure of the relative ease with which the reader processes the text. If early eye movements can account for variation in later word reading skill in this setting, that insight could have theoretical and practical implications. First, it is a contribution to our understanding of eye movements of developing readers, which is still limited. The gap in the literature concerns developing readers in any context, and data from naturalistic settings is scarce. Few, if any, studies have investigated to what extent early eye movements during reading predict later word reading ability in children in this context. Ultimately, eye movement analysis could inform the identification of children needing extra support in early reading development. Encumbered word level processes can have implications for reading comprehension and the importance of early identification of children with poor word reading and poor predicted development cannot be overstated (Rayner et al., 2009; Perfetti, 2010). Further, the benefits of predicting word reading ability extend to a wider perspective, as improved assessment could assist specialized support also for proficient readers.

This study springs from a research project developing an eye-tracking and AI-based screening method for reading difficulties (RD) described by Ygge et al. (2016), intended for use in the school environment. All participants were recorded in their schools. Eye movement analysis was based on normal text reading and a word reading assessment was carried out to establish their reading proficiency. Thus, the present analysis examines data collected during this large-scale, data driven research project ($n = 2{,}687$) which provides the methodological context of this paper (Strandberg et al., 2022).

In this study, we analyze to what extent children's eye movements during reading predict word reading ability tested the same year and compare the results to predictions of word reading skill one year later. To our best knowledge, it has not been done before with this approach and in this setting. It seems plausible that eye movements will explain some of the variance in word reading ability measured at the same occasion. It is more uncertain, however, whether it is possible to make long-term predictions about word reading ability, such as one year later. Presumably, the amount of variance explained by the eye movement measures decreases the longer the time that has passed between the time of recording and the estimation of word reading ability, although we currently do not know by how much. Therefore, it is of interest to compare the variance explained the first year to the second occasion one year later, in order to get a quantitative estimation of the predictive validity of eye movements. Due to a lack of studies of immediate relevance, it is unfeasible to build supported hypotheses based on findings directly linked to our questions.

However, previous results from this field lead us to anticipate a bigger difference in explained variance between the concurrent and longitudinal model in the group of youngest participants (i.e., those who were in first grade at the time of eye movement recording; referred to as sample A and B in the analysis and onward, for the sake of clarity). That means, we expect the variance in word reading ability that can be ascribed to the eye movement model to decrease more longitudinally among the younger readers. Primarily, because we anticipate the eye movement behavior of this group to be influenced by a transition from sub-lexical to lexical processing, which is known to affect the eye movement characteristics during reading (Reichle et al., 2013b). Also, we expect higher variability among the eye movement measures in first grade students and because the youngest students may be more susceptible to other factors that influence the reliability of the eye movement recording and/or word reading assessment. Finally, the duration of their access to sufficient instruction is more uncertain (whereas the second grade students have had at least one year of formal instruction, which we deem enough to establish the basic concepts of word reading, at least). We address the following three key questions:

(1) To what extent do eye movements recorded in first and second grade predict word reading ability at the time of recording and 1 year later? (2), Does the amount of explained variance in word reading ability decrease in the longitudinal model compared to predictions made the same year and if so, by how much? (3) Is the decrease larger in either sample?

2. Methods

2.1. Participants

The participants were elementary school students in Järfälla municipality in Stockholm, Sweden (see Table 1 for detailed information). They all went to public schools (all municipally governed elementary schools were enrolled in the study). The yearly income of Järfälla's population was slightly higher than the Swedish median. The unemployment rate was lower than the Swedish median percentage (SCB, 2023). The participants were singled out from the larger sample and included in the present analysis on the basis of having completed all tasks of the word reading assessment and having participated twice with a one-year-interval, either in first and second grade or second and third grade (2015 and 2016).

No children with intellectual disability (IQ < 70) or general learning disabilities were part of the sample, as they attend classes with

TABLE 1 Participant information.

	Sample A	Sample B
Girls (*n*=)	84	97
Boys (*n*=)	79	107
N/A	1	1
Total (*N*=)	164	205
Age M1 m (sd)	7.9	8.8
Age M2 m (sd)	8.8	9.8

M1 refers to the first cycle of data collection (spring semester of 2015) and M2 to the second cycle of data collection (spring semester of 2016).

TABLE 2 Details about language, background and Caregivers' educational level among elementary school students in Järfälla.

	% of all students		
	Swedish L2	FB	HE
Trosa	4.7	12	51
Järfälla	11.2	34	61
Sweden	10.6	24	57

Swedish L2, Swedish as a second language; FB, Foreign background (the participant was born abroad or was born in Sweden to caregivers born abroad); HE, higher education among caregivers (completed third cycle education or higher).

TABLE 3 Results on the National Tests (reading subtests only) in Swedish among third graders 2016.

	Fiction	Fact	Oral	Discourse
Trosa	91.9	93.3	93.2	96.2
Järfälla	94.9	94.9	96.6	97.3
Sweden	92.5	93.8	96.1	97.2

Percentage of participants whose test results corresponded to curriculum learning goals. Fiction, Silent reading of fiction; Fact, Silent reading of fact based text; Oral, Oral reading; Discourse, Verbal text discourse.

adjusted curriculum and syllabus. Readers with Swedish as first and second language cannot be differentiated in the current study. Public records indicate that the proportion of students with Swedish as a second language was marginally larger in Järfälla public elementary schools than the Swedish average (SCB, 2023; see Table 2 for more information).

The national tests are compulsory exams which Swedish children take in third, sixth and ninth grade of elementary and middle school, and again in high school. The purpose of the tests is to support teachers' assessments of students in certain subjects in accordance to goals stated in the national curricula. Information gleaned from the test results is also used for comparison of the relative attainment of students in different schools and areas. Downloadable information in English about the national test is available on the Swedish National Agency of Education's website (Skolverket, 2023). Indicative of the general reading performance among the third grade students in this study, Table 3 shows the third grade students' 2016 results on the reading subtests of the national tests in Järfälla, as well as the national average.

2.2. Ethical considerations

The research protocol of the current study is approved by the Central Ethical Review Board (Ö 13/2015). Prior to data collection, the supervising researchers (Mattias Nilsson and Gustaf Öqvist Seimyr) met with the principals, teachers and caregivers involved at parent-teacher meetings and informed them about the study. Further information and forms for written consent were sent to the residence of all caregivers. All children enrolled in first, second and third grade were offered to participate, provided that parental consent was acquired. Moreover, their personal consent was obtained at the time of testing, and they were informed they may terminate their participation at any moment. No formal exclusion criteria were applied, but all participants were enrolled in schools with standard curriculum and syllabus, i.e., no students in special educations programs participated in the study.

2.3. Apparatus and procedure

In order to maintain authentic conditions for data collection, the testing and recording were carried out in the child's every-day environment. The participants' eye movements were recorded during normal text passage reading in an unrestrained, binocular eye tracking set-up. Thus, no devices that limit head movements were used.

The participants completed five different tasks: Word Chains, Rapid Automatized naming (RAN), word reading, pseudo word reading, and text reading (the two text passages constituting the text reading assignment are considered as part of one and the same task). Eye movements were not recorded during the first assignment (Word Chains), which was conducted in the classroom in accordance with the instruction handbook. The remainder of the assignments (RAN, word reading, pseudo word reading and text reading) was completed individually, together with an experiment leader in a separate room. The participants were called out one by one from their classroom activity. In the adjacent room where the recording took place, they were seated at approximately 70 centimeters from the monitor. Before the start of the experiment, a five-point calibration procedure was performed on the monitor of a Tobii T120 eye tracker (120 Hz; Tobii Technology AB, Danderyd, Sweden) with a 1280*1024 screen resolution. The children were given step-by-step information in the beginning assignment and throughout the assignment at relevant times. The personal consent of each participating child was obtained. The tasks were presented sequentially and run with the software Optoscope (version 3.0.0.19). Participants could terminate their participation at any time. Where applicable, data recorded before this point was saved for analysis. Note that while eye movements were recorded during each task (except Word Chains) only eye movements during text reading are analyzed in the present paper. Sound was recorded with an external USB microphone (Samsung GoMic). All tests (RAN, word reading, pseudo word reading, text reading) were scored and analyzed as described below and constituted parts of the word reading assessment.

2.4. Stimulus material

The word reading assessment in its entirety is found in Supplementary Figures S1–S10. Below, the word reading assessment is described in chronological order (e.g., the first task was Word Chains and so forth).

2.4.1. Word chains

Word Chains is a standardized test used to assess children's visual word recognition. It requires the participant to separate words from each other when presented in series of strings (i.e., written consecutively, without blank spaces). The test involves 80 three-word-strings. The word strings consist of nouns, adjectives and verbs intermingled and the task is to mark the boundaries between words with a pencil. The participants were instructed to work through as many strings as possible within the time limit of 2 min. This assignment was carried out in the class room setting and is a part of a special edition of Läskedjor-2 (Jacobson 2015).

TABLE 4 Text passage metrics.

Grade	W (n)	WL (m)	LW (n)	S (n)	SL (m)	% long words	LIX	TTR %	OVIX	OVR %
1st										
Text A	20	3.6	0	5	4	0	4	80	41.7	92.55
Text B	20	3.6	0	5	4	0	4	80	41.7	92.55
2nd										
Text A	42	3.8	1	7	6	2.38	8	76.19	53.22	92.72
Text B	42	3.8	1	7	6	2.38	8	76.19	53.22	92.72
3rd										
Text A	60	3.85	6	11	5.45	10	15	68.33	46.04	90.7
Text B	60	3.85	6	11	5.45	10	15	68.33	46.04	90.7

W, words; WL, word length, (n) letters/(n) words; LW, long words > 6 letters; S, sentences; SL, sentence length (n) words/(n) sentences; % of long words, long words/words*100; LIX, SL + percent long words; TTR, type/token ratio; OVIX, log (tokens)/log [2-log (types)/log (tokens)]; OVR, log (types)/log (tokens).
LIX is an abbreviation of läsbarhetsindex in Swedish, which translates to readability index in English. Type/token ratio is a measure of lexical density. OVIX is an abbreviation of ordvariationsindex in Swedish which takes consideration of total text length and translates to word variation index in English. OVR is an abbreviation of ordvariationsratio in Swedish, which translates to word variation ratio.

2.4.2. Rapid automatized naming

This and the subsequent tasks (described below) were presented on the Tobii T120 screen. The alphabetical, serial format rapid naming task was based on the Comprehensive Test of Phonological Processing (CTOPP-II; Wagner et al., 2013) which taps into the reader's processing speed and fluency. It consists of 4 rows of 9 letters each, in black on white background. Participants were to name the presented letters consecutively as fast as possible. Due to time limitations, only a letter naming task was included in the present study. The responses were recorded with an external USB-microphone (Samson, Go Mic). The total naming time was recorded and reanalyzed in terms of named letters per minute.

2.4.3. Word and pseudo word reading

The tests were not part of any standardized test protocol, but were developed in accordance with the principles of Test of Word Reading Efficiency (TOWRE; Torgesen et al., 2012) which is a word reading test in English. The outcomes were intended to reflect word recognition accuracy and phonological decoding. 64 words were presented in rows of 8 × 8 in black on white background. They were ordered by increasing length and decreasing frequency, starting with some of the most common two-letter words and ending with nine-letter words. The pseudo words were presented in the same manner, ordered by increasing length. The pseudo words were constructed based on the real words according to a system developed by Gustaf Öqvist Seimyr. The objective was to create pseudo words that were similar to real words in terms of phonetic complexity. The consonants n, l and m were replaced by l, m and n, respectively. Vowels were replaced in according to place of articulation: (a- > o, o- > å, å- > u, u- > a), and (e- > i, i- > y, y- > ö, ö - > ä, ä- > e). This procedure was repeated if a word was still semantically coherent after the first transposition. The participants were instructed to read as many words/pseudo words out loud as possible. Their responses were recorded and the number of accurate items within the time limit of 30 s per test was noted.

2.4.4. Text reading

The participants were asked to read two short fictional texts in Swedish. The texts consisted of one-passage paragraphs presented in black text on white background. We wanted to incite the gaze behavior associated with a natural reading situation. Therefore we considered it suitable to adapt the level of difficulty to what the participants normally would read. This has implications for group comparisons. However, by varying the stimuli we avoid unbalanced results which using identical text passages for all students would lead to (disproportionate processing difficulties for participants in first grade or ceiling effects among participants in third grade). In collaboration with a special educations teacher, the authors developed three sets of texts adapted to grade and presumed approximate reading ability, guided by the amount of reading instruction received. Children start receiving formal training in basic skills necessary for reading in the last year of preschool (at approximately 6 years of age). Despite this, there is great variation in reading and writing competence among children who start first grade. In Strandberg et al., 2022 this text reading task (as well as the remainder of the word reading assignment) was used in a sample of 2,876 children and descriptive data, correlation coefficients and linear mixed models are reported. The text passages are described in further detail in Table 4. The texts all dealt with everyday topics. The participants were informed on beforehand that one question about the content would follow upon them finishing each text. The questions were of simple yes- or no character and the answer was evident in the texts (no inferences were required on the student's behalf). The purpose of the questions was to encourage attentive reading. The participants' answers did not provide information pertinent to assess reading comprehension. Thus, their answers are not analyzed further in the present study. The participants were encouraged to read silently if possible, but reading aloud was allowed when requested by the child. Reading speed was measured by the number of read words per minute and the result of both texts was averaged. The eye movement measures in this study are based on this tasks.

2.5. Analysis

Eye movements were recorded and analyzed binocularly. The eye movement data was analyzed in Optosphere (Version 2.1) (Nilsson Benfatto et al., 2016). The software classifies the eye movements as events, depending on their properties. A fixation was defined as the event of the eye remaining within an area corresponding to the fovea

TABLE 5 Descriptive statistics of eye movement variables.

	Sample A, m (sd)	Sample B, m (sd)
	1	2
Mean fixation duration (milliseconds)	519 (185)	349 (102)
Forward saccade amplitude (degrees)	0.74 (0.19)	0.95 (0.26)
Proportion of regressions (ratio)	0.33 (0.05)	0.21 (0.06)

The variables are based on eye movement recordings made in first grade in Sample A and second grade in group Sample B (e.g., recorded during first cycle of data collection). Correlations between eye movement variables in each sample.

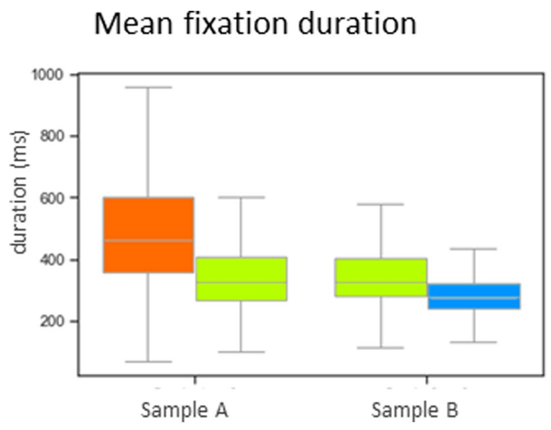

FIGURE 1
Mean fixation duration during text reading. Data from the first cycle is visualized in the left box and data from second cycle in the right box.

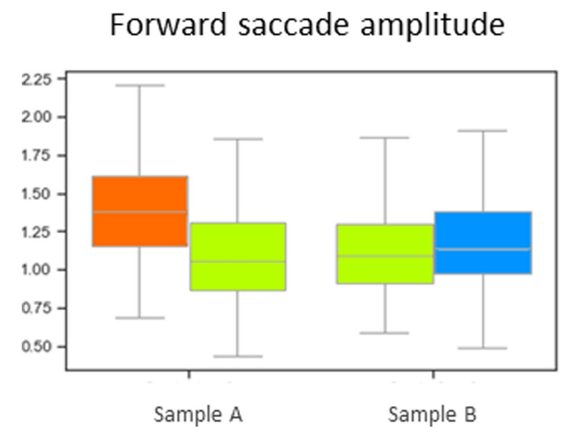

FIGURE 2
Mean forward saccade amplitude during text reading. Data from the first cycle is visualized in the left box and data from second cycle in the right box.

for at least 50 ms. Saccades were classified according to whether they occur within or outside the perceptual span and are identified as progressive (45–224 degrees) or regressive (224–45 degrees) depending on their directional angle. Fixations were analyzed in terms of mean fixation duration. Saccades were analyzed according to directional angle, amplitude and proportion of regressive saccades (Ygge et al., 2016). See Table 5 and Figures 1–3 for the descriptive statistics and distribution of eye movement data and Table 6 for the descriptive statistics of the word reading assessment.

The sample was separated in two groups based on which grade the participant attended. Throughout the remainder of this paper, we refer to the group of children who participated in first and again in second grade as sample A, while the group of children who participated in second and third grade is referred to as sample B. At the outset of data analysis, the entire sample consisted of 561 participants. The data was filtered according to a three-step procedure. Eye movement recordings were removed if the amount of noise exceeded 25% ($n = 178$). Next, subjects were excluded based on whether the difference in reading speed (WPM) between the two text conditions exceeded the outlier threshold values ($n = 8$). Outlier values in the eye movement data were then identified with Tukey's interquartile range with the scale factor set to 3.0. Following the complete filtering procedure, 164 participants remained in sample A and 206 participants remained in sample B.

2.5.1. Outcome variable

To generate a representative measurement of reading ability, we combined the outcomes of the reading assessment in one, composite variable. We standardized the results through z-transformation and combined them using simple averaging. The tests are described under Materials, above.

We carried out this analysis based on the assumption that the tests (1) assess important constructs of reading ability, (2) to some extent are conceptually linked and (3) provide a global representation of reading ability. Moreover, they are relevant constituents of reading assessments. Our intention was to facilitate interpretation of results pertaining to multiple variables

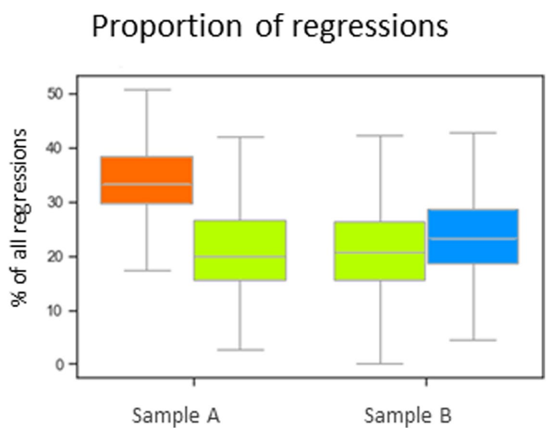

FIGURE 3
Mean proportion of regressions during text reading. Data from the first cycle is visualized in the left box and data from second cycle in the right box.

TABLE 6 Descriptive statistics of word reading assessment.

Grade	Sample A, m (sd)		Sample B, m (sd)	
	1	2	2	3
Rapid naming	79 (18)	100 (20)	97 (19)	112 (20)
Word chains	10 (6)	18 (7)	17 (6)	24 (7)
Pseudo word reading	16 (7)	23 (6)	22 (6)	26 (6)
Word reading	28 (11)	39 (10)	39 (10)	46 (9)
Reading speed	56 (29)	104 (39)	103 (40)	139 (40)

Rapid naming is estimated in letters per second and reading speed is estimated in words per minute (during text reading) while the remaining tests are evaluated in number of correct responses.

TABLE 7 Intercorrelations word reading assessment in first grade (sample A).

	1	2	3	4	5
1. Rapid naming		0.37***	0.43***	0.52***	0.51***
2. Word chains			0.58***	0.65***	0.72***
3. Pseudo word reading				0.86***	0.75***
4. Word reading					0.88***
5. Reading speed					

*$p < 0.05$, **$p < 0.01$, ***$p < 0.001$.

TABLE 8 Intercorrelations word reading assessment in second grade (sample A).

	1	2	3	4	5
1. Rapid naming		0.22**	0.45***	0.55***	0.43***
2. Word chains			0.49***	0.60***	0.58***
3. Pseudo word reading				0.77***	0.55***
4. Word reading					0.77***
5. Reading speed					

*$p < 0.05$, **$p < 0.01$, ***$p < 0.001$.

and to generate a robust, conceptually valid measure. The interaction of eye movement variables and each of the reading tests was analyzed (see Supplementary Table S1). The main finding of this prelusive, exploratory analysis is that the predictor variables account for less variance in three of the outcome variables (RAN, word chains, and pseudo word reading) when those tests are handled separately. The predictor variables account for slightly less of the variance in word reading accuracy and approximately the same amount of variance in reading speed as in the composite measure. Largely, these findings support the integrity of the composite measure. They indicate that combining these outcome variables does not compromise nor exaggerate the predictive validity of the model. There are no notable differences between the individual tests and the composite measure in terms of longitudinal differences.

The variance inflation factor (VIF) was calculated in order to investigate the influence of multicollinearity among the predictor variables. The variance inflation factor was <2.5 for all predictors in both samples and multicollinearity should therefore only affect the variance of the regression coefficients to a limited extent (Thompson et al., 2017).

A multiple linear regression was calculated to predict and account for the variance in the composite word reading ability score (OV) based on eye movement measures (PV). Eye movements recorded in first grade were used as predictive variables for word reading ability assessed the same year (i.e., assessed at the same occasion as eye movement recording took place) and 1 year post-recording (i.e., when the students were in second grade). The same analysis was carried out in sample B - eye movements recorded in second grade were used as predictive variables for word reading ability assessed the same year and 1 year post-recording.

3. Results

Inter−/correlations of the word reading assessment (including the composite measure) are described in Tables 7–12.

Below, we introduce the models of eye movement variables predicting word reading ability recorded at the same occasion. Second, we address predictions of word reading ability 1 year post eye movement recordings.

TABLE 9 Intercorrelations word reading assessment in second grade (sample B).

	1	2	3	4	5
1. Rapid naming		0.37***	0.51***	0.59***	0.49***
2. Word chains			0.58***	0.66***	0.68***
3. Pseudo word reading				0.82***	0.7***
4. Word reading					0.81***
5. Reading speed					

*$p < 0.05$, **$p < 0.01$, ***$p < 0.001$.

TABLE 10 Intercorrelations word reading assessment in third grade (sample B).

	1	2	3	4	5
1. Rapid naming		0.31***	0.42***	0.54***	0.35***
2. Word chains			0.48***	0.54***	0.59***
3. Pseudo word reading				0.76***	0.60***
4. Word reading					0.68***
5. Reading speed					

*$p < 0.05$, **$p < 0.01$, ***$p < 0.001$.

TABLE 11 Correlations word reading assessment in first x second grade (sample A).

	1	2	3	4	5	6
1. Rapid naming	0.58***	0.38***	0.31***	0.43***	0.39***	–
2. Word chains		0.74***	0.38***	0.51***	0.56***	–
3. Pseudo word reading			0.72***	0.73***	0.61***	–
4. Word reading				0.8***	0.74***	–
5. Reading speed					0.79***	–
6. Composite variable						0.85***

*$p < 0.05$, **$p < 0.01$, ***$p < 0.001$.

TABLE 12 Correlations word reading assessment in second x third grade (sample B).

	1	2	3	4	5	6
1. Rapid naming	0.61***	0.42***	0.45***	0.57***	0.43***	
2. Word chains		0.79***	0.47***	0.51***	0.61***	
3. Pseudo word reading			0.82***	0.73***	0.59***	
4. Word reading				0.82***	0.75***	
5. Reading speed					0.79***	
6. Composite variable						0.88***

*$p < 0.05$, **$p < 0.01$, ***$p < 0.001$.

3.1. Concurrent analysis: predictions of word reading ability based on eye movements recorded the same year

3.1.1. Sample A

A significant regression equation was found [F (3,160) = 80.64, $p < 0.001$]. Eye movements recorded in first grade accounted for 59% of the variance in word reading ability score in first grade ($R^2 = 0.6$, $R^2_{Adjusted} = 0.59$). Mean fixation duration and forward saccade amplitude were significant predictors of word reading ability score. The model shows that an increase of mean fixation duration and proportion of regression is associated to a decrease in outcome variable, while an increase of saccade amplitude is linked to a higher word reading ability score (see Table 13).

3.1.2. Sample B

A significant regression equation was found [F (3, 202) = 107, $p < 0.001$]. Eye movements recorded in second grade accounted for 61% of the variance in word reading ability score in second grade ($R^2 = 0.61$, $R^2_{Adjusted} = 0.61$). Each variable in the model was a significant predictor of word reading ability score. The model shows that an increase of mean fixation duration and proportion of regression is associated to a decrease in outcome variable, while an increase of saccade amplitude is linked to a higher word reading ability score (see Table 14).

TABLE 13 Summary of multiple regression analysis: reading ability in first grade predicted by eye movements variables in first grade.

	Estimate	Std. error	*t*-value	*P* (>|t|)
(Intercept)	115.01	13.02	8.83	1.74e-15 ***
Mean fixation duration	−0.10	0.01	−10.72	< 2e-16 ***
Forward saccade amplitude	29.13	9.45	3.08	0.00242 **
Proportion of regressions	−82.33	29.63	−2.78	0.00612 **

Outcome variable: Composite measure of reading assessment outcomes in first grade. Multiple R-squared: 0.69. Adjusted R-squared: 0.59. $p<0.001$. Significance codes: *$p<0.05$, **$p<0.01$, ***$p<0.001$.

TABLE 14 Summary of multiple regression analysis: reading ability in second grade predicted by eye movement variables in second grade.

	Estimate	Std. error	*t*-value	*P* (>|t|)
(Intercept)	148.82	14.14	10.52	< 2e-16***
Mean fixation duration	−0.2	0.02	−9.73	< 2e-16***
Forward saccade amplitude	57.36	8.49	6.76	1.47e-10***
Proportion of regressions	−150.11	29.13	−5.15	6.09e-07***

Note. Outcome variable: composite measure of reading assessment outcomes in second grade. Multiple R-squared: 0.61. Adjusted R-squared: 0.61. $p<0.001$. Significance codes: *$p<0.05$, **$p<0.01$, ***$p<0.001$.

TABLE 15 Summary of multiple regression analysis: reading ability in second grade predicted by eye movement variables in first grade.

	Estimate	Std. Error	*t*-value	*P* (>|t|)
(Intercept)	161.93	20.56	7.88	4.86e-13***
Mean fixation duration	−0.11	0.01	−7.64	1.84e-12***
Forward saccade amplitude	38.47	14.92	2.6	0.0108*
Proportion of regressions	−82.61	46.78	−1.76	0.0793

Outcome variable: composite measure of reading assessment outcomes in second grade. Predictor variables are based on recordings from first grade. Multiple R-squared: 0.45. Adjusted R-squared: 0.44. $p<0.001$. Significance codes: $p<0.1$, *$p<0.05$, **$p<0.01$, ***$p<0.00$.

TABLE 16 Summary of multiple regression analysis: word reading ability in third grade predicted by eye movement variables in second grade.

	Estimate	Std. Error	*t*-value	*P* (>|t|)
(Intercept)	175.24	16.38	10.7	< 2e-16***
Mean fixation duration	−0.19	0.02	−7.86	2.28e-13 ***
Forward saccade amplitude	43.9	9.83	4.5	1.33e-05 ***
Proportion of regressions	−100.76	33.75	−2.96	0.00318 **

Outcome variable: composite measure of reading assessment outcomes in third grade. Predictor variables are based on recordings from second grade. Multiple R-squared: 0.48. Adjusted R-squared: 0.48. $p<0.01$. Significance codes: *$p<0.05$, **$p<0.01$, ***$p<0.00$.

3.2. Longitudinal analysis: predictions of word reading ability based on eye movements recorded one year earlier

3.2.1. Sample A

A significant regression equation was found [F (3, 160) = 43.41, $p<0.001$]. Eye movements recorded in first grade accounted for 44% of the variance in word reading ability score among second grade students ($R^2=0.45$, $R^2_{Adjusted}=0.44$). Mean fixation duration and forward saccade amplitude were individually significant predictors of word reading ability score. The model shows that an increase of mean fixation duration and proportion of regression is associated to a decrease in outcome variable, while an increase of saccade amplitude is linked to a higher word reading ability score (see Table 15).

3.2.2. Sample B

A significant regression equation was found [F (3, 202) = 63.23, $p<0.001$]. Eye movements recorded in second grade accounted for 48% of the variance in word reading ability score in third grade ($R^2=0.49$, $R^2_{Adjusted}=0.48$). All eye movement measures in the model were significant predictors of word reading ability. The model shows that an increase of mean fixation duration and proportion of regression is associated to a decrease in outcome variable, while an increase of saccade amplitude is linked to a higher word reading ability score (see Table 16).

Eye movements recorded in first grade predicted 59% of the variance in the children's word reading ability the same year, while it accounted for 44% of the variance one year later. In sample B, eye movements recorded in second grade explained 61% of the variance in word reading ability measured the same year, and 48% one year later. Thus, the explained variance decreases with 15 percentage points between first and second grade, and with 13 percentage points between second and third grade. Further analysis showed that r^2 is substantially dependent on mean fixation duration in each instance while forward saccade amplitude and proportion of regressions contribute to the models to a lesser extent. As a unique predictor, mean fixation duration accounts for on average 53% of the variance in concurrent word reading ability and 42% on year post-recording. Thus, the exclusion of the forward saccade amplitude and proportion of regression two did influence r^2 negatively, albeit to a small extent. The initial model including all three variables was deemed to best predict word reading ability score.

The texts which constituted the text reading task were adapted to an approximated level of reading proficiency associated with each grade (e.g., participant age). Consequently, the participants read different texts in the first vs. second cycle of data collection. In terms of the present investigation, the eye movement variables and reading speed (WPM, which was entered in the composite variable) are based on the same text in the analysis of concurrent word reading ability. Exclusion of reading speed from the composite measure would eliminate the risk of interdependence between those variables. Theoretically, however, it would make for a less sound representation of natural reading. It would narrow the scope of the composite variable to a representation mainly of lexical level word reading (of word lists), which is unintuitive from a logical and conceptual standpoint. The objective of this paper is to investigate to what extent eye movements account for variation in word reading ability, and reading speed is typically indicative of proficiency (Sovik et al., 2000). We ran an additional analysis to determine the effects of exclusion of reading speed from the composite variable. The exclusion of reading speed affected *r2* in such a way that eye movements were on average 9 percentage points less predictive of word reading ability ($R^2_{Adjusted}$ = 0.53 in sample A and 0.49 in sample B). As participants had graduated and enrolled in the subsequent grade by the time of the second cycle of data collection, the overlap does not exist in the longitudinal models. Thus, based on an unrelated text, eye movements accounted for on average 48% of the variation in word reading ability measured 1 year later. Based on conceptual assumptions and the fact that there only was a nine percentage point difference related to the inclusion or exclusion of reading speed in the concurrent model, we opted to incorporate it as a measure in the composite variable of word reading ability.

4. Discussion

The objective of this study was to investigate to what extent eye movements during reading predict later word reading ability in young readers. We were interested in examining this relationship in a large and naturally diverse sample under as ecological circumstances as possible. With this in mind, we analyzed the extent to which three basic eye movement measures predicted the variance in word reading ability, both concurrently and longitudinally.

4.1. General discussion of descriptive eye movement findings

A pattern of quite robust associations between the composite variable and the eye movement variables emerge in our data. In summary, an increase of the composite variable was associated to shorter fixations, longer forward saccades, and fewer regressions during reading. This means that a higher result on the variable intended to reflect word reading ability was linked to changes in eye movements that are consistent with improved text processing (Blythe, 2014).

Turning to the relationship between the eye movement variables in this study and those reported in earlier work, we found some variation that appears to highlight the difference of approach between our study and the lion's share of past research. Compared to several prior studies (Rayner, 1986; Blythe et al., 2006, 2009; Reichle et al., 2013; Rau et al., 2015b) mean fixation duration was higher in both sample A and sample B. Increased variation among variables can be a product of a naturalistic set-up and diverse sample of participants. In this case, children with Swedish as a second language and children with rudimentary reading skill were included. Additionally, we collected the data at the location of the schools, to fulfill the intention to record the students as they normally would read. Finally, tasks with unlimited time and text-level stimuli, by their nature, involve more freedom in when and how to move the eyes than time-limited reading of, for example, single sentences or words. Typically, forward saccade length increases with age and reading development (Rayner, 1986; Blythe, 2014). In this case, forward saccade length was 0.74 degrees in first grade and 0.95 degrees in second grade (i.e., in sample A and B, respectively). This leads us to believe that our text passages were appropriately adapted to the participants' age and presumptive reading proficiency. The first grade students read texts containing line-breaks at the end of each sentence, whereas sentences appeared consecutively in the texts for second grade students. Words and sentences were longer and semantically more advanced for the children in second grade. We were careful so as not to exaggerate these factors, as we wanted the children to be able to process the texts, given that their reading ability was age adequate. Proportion of regression decreased, as expected according to the literature, although the prevalence and role of regressions vary depending on the context. Characteristics of the supposed incongruence that the reader experiences as well as the orthographic transparency influence if and how they reread a part of the text (Rau et al., 2015a; Inhoff et al., 2019). The significance of regressive saccades in this analysis is further discussed on page 17. Structured control conditions could reveal more about the influence of these and similar stimuli characteristics in future work.

4.2. Concurrent predictions of word reading ability

Eye movements accounted for more or less the same amount of variance in concurrent word reading ability in sample A and sample B (i.e., in first compared to second grade; the difference was 1 percentage point). Overall, average fixation duration was the most important predictor of later and concurrent word reading ability. Saccade amplitude and proportion of regressions contributed to the models but to a lesser extent. The average proportion of regressions generally was within the expected range, but was not a significant predictor of longitudinal word reading ability in the youngest readers. This suggests that early on, when children often read out each word slowly in turn, the number of regressive saccades is not informative, or at least not significantly so, in terms of word reading ability. Further, it is important to consider the qualities of the variable. In this analysis, proportion of regressions was based on the recording as a whole and does not take details of the context in which they occur into account. The proportion of regressive saccades reveals nothing of the length of the regression or if they occur within or across several words. The properties of the word that the reader rereads are important to the interpretation of why the reader moves the gaze backwards (Inhoff et al., 2019). Word-based eye movement measures could enable a deeper look at that issue in a future analysis. Speculatively, the fact that the first grade students (m age = 7.85) are in an early stage of reading acquisition plays a role. Their eye movement patterns (short forward saccades) suggest that they to some extent rely on small-unit decoding, which may lessen the need to reread text. Previous studies found that children reading in an orthographically opaque language (English) have higher rereading times than children reading in a transparent language (Rau et al., 2015b). Young readers of transparent orthographies tend to depend on sub-lexical processes for word recognition which may limit the need and prevalence of regressions. Regressions may therefore be of limited value to the assessment of word reading ability in very young readers, as small-unit decoding is usually reliable in a somewhat transparent language such as Swedish. Our results show that while the participants in first grade did make regressions to an expected extent, they did not account for variance in word reading ability to any significant degree. As small unit decoding is reliable, processing difficulties associated to RD might be reflected in variations in other variables in the youngest readers. Future work could further investigate what eye movement characteristics that differentiate students with RD from students who are slow to acquire the first steps of reading but over time progress to the level of readers with typical reading development.

4.3. Longitudinal predictions of word reading ability

We expected the eye movement variables to predict variance in word reading ability score to a lesser extent 1 year post-recording, compared to the models of eye movements and concurrent word reading ability. In line with that assumption, $R^2_{Adjusted}$ was lower in the longitudinal predictions in both samples of students. While the model predicts roughly 60% of the variance in concurrent word reading ability, the explained variance is on average 14 percentage points lower 1 year later. This means that eye movements accounted for less of the variation in word reading ability 1 year after the recording, however, we consider the decrease small seeing as it is based on an unrelated text and a year has passed between predictions. We consider this finding as further indication (see page 15) that the predictions were not unduly biased by the fact that reading speed and eye movement measures were recorded from the same text stimuli in concurrent analysis. The fact that the decrease in explained variance is small when the predictor variables are based on an unrelated text speaks to their validity as reflections of global reading ability rather than to text-specific characteristics.

Considering the relation between the samples of participants, we found that the difference between the concurrent and longitudinal models are greatest in sample A (that is, in the group of students whose eye movements were recorded in first grade). Similarly, there is a somewhat greater difference in word reading assessment outcomes between first and second grade, in relation to second and third grade. Assuming that there is a tight interaction between word reading and lexical processing, this pattern can be mapped onto a shift of decoding strategy, and its' interplay with sub-lexical and lexical processes. As the young readers begin to integrate lexically based processes in their reading, eye movements in first grade may be reflective of a decoding strategy which is less used by second grade.

In future work it would be interesting to consider the influence of reading proficiency on predictions of word reading ability based on eye movements. In this area, interesting work has been carried out by Vorstius et al. (2014) who found that the relationship between eye movement variables and reading ability was weaker among poor readers, especially those with results below the 0.3 quantile. The predictability of word reading ability may decrease at different rates across individuals, why it would be valuable to compare the predicted values to the actual outcomes in children and analyze possible interactions with reading proficiency.

There are some implications worth noting with regards to the present study. Pursuant to our objectives, we analyzed data recorded in an authentic environment where simplicity and ecological validity was prioritized. This was part of an explorative approach which allowed a high number of students to participate. Further, we chose an inclusive approach regarding the sample because we wanted collect data from a typical group of elementary school students, aware that it has implications for the outcomes and conclusions in this study. Indeed, the results reflect variation among the variables that is consistent with limited experimental control and the findings should be considered with this in mind. There are several interesting variables that could be taken into account regarding the participants for a fine-grained analysis of the relationships reported here, such as mother tongue and presence of specific learning difficulties (such as RD). Further, both the model and materials for assessments should be developed for more precise predictions. In future work, additional data points would enable valid growth modeling. It would be interesting to include word-based eye movements, which we think could improve the models while also inform assessments about variations in underlying processes during reading. For educational purposes, both basic and word-based eye movements could be used to infer precise information about strengths and weaknesses in a child's reading. As an example, information about word recognition efficacy can be inferred from the relationship between fixation durations and word frequency.

Small unit decoding, which can encumber fluent reading, could be revealed through analysis of the saccade pattern and also at what level of complexity that the reader resorts to this strategy.

Nevertheless, the data in the present paper can reproduce previously well-known findings and relationships between eye movements, word reading ability and age differences. Here, we have shown that eye movements collected in a natural school setting with limited experimental control can account for a large portion of variance in word reading ability, not only concurrently, but also 1 year after the recordings were made. This suggests that eye tracking could be a potentially useful and efficient complementary technique for monitoring and predicting children's word reading development during the early school years. Children with a predicted poor developmental reading trajectory might then be given professional support early on and minimize the effect on school performance, motivation, and self-esteem.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Ethics statement

The studies involving human participants were reviewed and approved by the Central Ethical Review Board (Ö 13/2015). Written informed consent to participate in this study was provided by the participants' legal guardian/next of kin.

Author contributions

AS, MN, and GÖ contributed to the conception and design of the study, and performed the word reading assessment and eye tracking recordings. MN and GÖ processed the eye movement data. AS and MN performed the statistical analysis and wrote the draft of the manuscript. All authors contributed to manuscript revision, read, and approved the submitted version.

Funding

This work was supported by the Sweden's innovation agency, VINNOVA, under Grant 2014–03459; the Sigvard and Marianne Bernadotte Research Foundation for Children's Eye Care and Ulla and Ingemar Dahlberg's Foundation.

Acknowledgments

The authors express their gratitude to the Sigvard and Marianne Bernadotte Research Foundation for Children's Eye Care, Ulla and Ingemar Dahlberg's Foundation, VINNOVA – Sweden's Innovation Agency and Trosa and Järfälla schools and municipalities for their support and contribution to this project.

Conflict of interest

MN and GÖ own equity in Optolexia, a company whose aim is to offer new technologies for the assessment of reading deficits in school-age children.

The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Supplementary material

The Supplementary material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/feduc.2023.1077882/full#supplementary-material

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