ResearchGate

See discussions, stats, and author profiles for this publication at: https://www.researchgate.net/publication/357378983

Exploring the Associations between Reading Skills and Eye Movements in Elementary Children's Silent Sentence Reading

Article *in* Reading Psychology · December 2021

DOI: 10.1080/02702711.2021.2020189

CITATIONS
3

READS
177

6 authors, including:

Sungyoon Lee
Middle Tennessee State University
10 PUBLICATIONS **114** CITATIONS
SEE PROFILE

Christopher Prickett
Driscoll Children's Hospital
3 PUBLICATIONS **14** CITATIONS
SEE PROFILE

Qinxin Shi
Children's National Hospital
17 PUBLICATIONS **161** CITATIONS
SEE PROFILE

Huilin Linda Sun
Syracuse University
9 PUBLICATIONS **116** CITATIONS
SEE PROFILE

All content following this page was uploaded by Sungyoon Lee on 18 December 2022.

The user has requested enhancement of the downloaded file.

Reading Psychology

ISSN: (Print) (Online) Journal homepage: https://www.tandfonline.com/loi/urpy20

Exploring the Associations between Reading Skills and Eye Movements in Elementary Children's Silent Sentence Reading

Sungyoon Lee, Steven Woltering, Christopher Prickett, Qinxin Shi, Huilin Sun & Julie L. Thompson

To cite this article: Sungyoon Lee, Steven Woltering, Christopher Prickett, Qinxin Shi, Huilin Sun & Julie L. Thompson (2022) Exploring the Associations between Reading Skills and Eye Movements in Elementary Children's Silent Sentence Reading, Reading Psychology, 43:1, 85-103, DOI: 10.1080/02702711.2021.2020189

To link to this article: https://doi.org/10.1080/02702711.2021.2020189

Published online: 28 Dec 2021.

Submit your article to this journal

Article views: 214

View related articles

View Crossmark data

Full Terms & Conditions of access and use can be found at
https://www.tandfonline.com/action/journalInformation?journalCode=urpy20

READING PSYCHOLOGY
2022, VOL. 43, NO. 1, 85–103
https://doi.org/10.1080/02702711.2021.2020189

Routledge
Taylor & Francis Group

Check for updates

Exploring the Associations between Reading Skills and Eye Movements in Elementary Children's Silent Sentence Reading

Sungyoon Lee[a], Steven Woltering[b], Christopher Prickett[b], Qinxin Shi[c], Huilin Sun[b] and Julie L. Thompson[b]

[a]Department of Elementary and Special Education, Middle Tennessee State University, Murfreesboro, Tennessee, USA; [b]Department of Educational Psychology, Texas A&M University, College Station, Texas, USA; [c]Department of Psychology, University of Utah, Salt Lake City, Utah, USA

ABSTRACT

The purpose of this study was to investigate the associations between elementary students' reading skills and their online reading (i.e., real-time reading) behaviors during silent sentence processing. Thirty-five students participated in this study and their eye movements were recorded during sentence reading tasks. The effects of students' reading skills measured by traditional standardized measures were investigated for widely-used eye tracking measures such as first fixation duration, gaze duration, regression path duration, total duration, word skipping, fixation count, and regression frequency. The eye tracking measures were chosen to represent early/late cognitive processes and temporal/spatial gaze behaviors. Linear mixed-effects regression analyses revealed that children's performances in reading skills predict most of the eye tracking measures.

ARTICLE HISTORY
Received 15 April 2021
Accepted 2 December 2021

Introduction

Well-developed reading skills are essential for children to be successful in later academic achievement as well as professional life (Alexander & Fox, 2008; Schroeder, Hyönä, & Liversedge, 2015). Since reading is a

CONTACT Steven Woltering swolte@tamu.edu Texas A&M University, Harrington Tower, 4232 TAMU, College Station, TX 77843-4232, USA.

© 2021 Taylor & Francis Group, LLC

complex and multi-dimensional activity that implies different component reading skills such as decoding, fluency, vocabulary knowledge, and comprehension (Kirby, 2007, National Reading Panel, 2000), it is essential for all those sub-skills to be well developed in the early stage of reading development (Schroeder et al., 2015).

One way to look at those reading skill development is using standardized test materials. These tests usually provide normed scores to understand where the students are in terms of their skill proficiencies. Another way to investigate the development is monitoring readers' eye movement patterns in real-time while students interact with textual information. This method has a particular benefit over using the outcome measures in that it gives researchers or educators the information of students' real-time reading behaviors. A few research studies have examined readers' reading processes reflected on their eye movements in relation to individual differences in reading development of adolescent and adult readers. However, the research focusing on elementary children's eye movements recently started to emerge. The present study aims to look at the relationships between reading skills and eye movements in elementary children using an advanced statistical analysis method.

Eye Movement Measures and Their Underlying Processes

In using the eye tracking technique in reading research, it is important to understand different eye movement measures and underlying linguistic/cognitive processes. Eye tracking research has developed various eye movement measures (or parameters), that have been fine-grained to indicate different cognitive processes (Conklin & Pellicer-Sánchez, 2016; Rayner, 1998; Zawoyski & Ardoin, 2019). For example, eye tracking measures often used to detect early or late cognitive processes in reading. It is suggested that durations of early fixations on a word are generally related to lower-level processes such as decoding or lexical access whereas durations of rereading or regressive saccadic movements are known sensitive to relatively higher-level processes such as syntactic integration or construction of a situational mental model that occurs relatively late in the reading processes (Rayner, 1998). Also, the eye movement measures are often categorized as duration or frequency measures in terms of its characteristics or properties. While duration measures are concerned with how long the reader's eye fixated on an Area of Interest (AOI), frequency measures represent how many times the eye movement events (e.g., fixations, saccades) are generated.

Previous studies have reported empirical evidence regarding the underlying cognitive processes in readers' eye movements. For example, it seems that gaze duration (i.e., the sum of all fixation durations on a word in

the first pass) is sensitive to the early cognitive process of a word such as decoding efficiency (De Leeuw, Segers, & Verhoeven, 2016a), while rereading duration (i.e., the total time spent reading a word or words minus first-pass reading duration) has been found to relate to later reading processes such as information integration (Raney, Campbell, & Bovee, 2014; Rayner, Pollatsek, Ashby, & Clifton, 2012). Regarding frequency measures, word skipping has been found to highly sensitive to textual properties such as word length, word frequency, and word predictability (e.g., Brysbaert, Drieghe, & Vitu, 2005; Huck, Thompson, Cruice, & Marshall, 2017; Rayner, Slattery, Drieghe, & Liversedge, 2011). Recently, reading researchers found that it may also be related to readers' reading skills such as word identification or reading comprehension (Barnes & Kim, 2016). Also, regressive saccades (i.e., backward eye movements) may reflect readers' attempts to solve integration problems by going back to previously fixated words (Rayner et al., 2012).

Relations between Reading Skills and Eye Movements Measures

In several previous studies, researchers often reported the relation between a particular reading skill and eye movement measures. For example, Rogers and Ardoin (2018) and Zawoyski and Ardoin (2019) reported negative correlations between children's oral reading fluency and various eye movement measures such as first fixation duration, gaze duration, total fixation time, and fixation counts. Also, De Leeuw et al. (2016a) reported that fourth graders' decoding ability was related to gaze duration and regressive eye movements. However, their primary research questions were not to investigate the relations between readers' reading skills and their eye movements.

A more comprehensive investigation that include a set of reading skill measures was done by Kuperman and Van Dyke (2011). The authors explored the associations between individual differences in a variety of reading skills and many eye movement measures with 16 – 24 year-old English speakers using multiple regression analyses. The participants took 18 verbal and cognitive skills assessments and read a series of sentences while their eye movements are monitored. The findings of this study were that rapid automatized naming and word identification are strongly associated with most of the eye movement measures. The results suggest that decoding ability put a heavy constraint on readers' comprehension processes.

Similarly, Foster, Ardoin, and Binder (2018) examined the associations with second grade elementary students. Examining the reliability and external validity of various eye movement measures, Foster et al. reported associations between a comprehensive set of reading skills and eye movement measures. According to the studies, eye movement measures are

generally associated with second grade students' reading fluency and their broad reading achievement. However, word skipping was not significantly related to any standardized measures. Additionally, it should be noted that the authors also found that duration measures are more reliable than frequency measures to reflect readers' reading development.

Although the past studies have directly or indirectly addressed the associations between reading skills and eye movements, there are a couple of limitations. First, Kuperman and Van Dyke (2011) used adolescent and early adult individuals as their study sample. In the present study, we are more interested in elementary students' eye movements in relation to their reading skill development. Second, Foster et al. (2018) and Kuperman and Van Dyke used correlation analyses and multiple regression analyses where many eye movement data points need to be averaged to a single number in order to indicate an individual's eye movement pattern. While examining the relationships, the present study uses a linear-mixed effects model that allows researchers better estimate the coefficients by modeling both fixed and random effects (Baayen, 2008).

Therefore, the present study sought to examine the associations between elementary students' reading skills and eye movement patterns in silent sentence reding using linear mixed-effects analyses. While examining the research question, we used a variety of eye movement measures including early/late and duration/frequency measures with a set of standardized measures for various reading skills. Also, the present study used sentence reading paradigm which has a long history in the field of psycholinguistics or cognitive psychology as a research method. The sentence reading task maximally reflects underlying cognitive processes while minimizing extra effects introduced by the task itself such as task demand effects (Nicol, Swinney, Love, & Hald, 2006).

Methods

Participants

Participants were a community sample of 42 children aged 7-10 recruited from a southwestern state in the United States during the Spring of 2017. To be included in the sample, the participants needed to be fluent in English. We excluded children who had severe developmental disorders (e.g., Autism Spectrum Disorders, ADHD, dyslexia) and/or did not have normal or corrected-to-normal vision. The data from five children were discarded from the present study because of poor data quality (more details below). Consequently, the final sample consisted of 35 children (mean age = 9.2; SD = 1.2) and had 20 boys

and 15 girls. Regarding language background, 18.9% were bilinguals. The children's ethnic background consisted of 13.5% Asian/Pacific Islander, 2.7% African-American, 18.9% Hispanic, 59.5% Caucasian, and 5.4% 'other'. Regarding socioeconomic status, 24.3% reported their annual income less than $50,000, 21.6% between $50,000 and $100,000, 48.6% more than $100,000, and 5.4% did not want to report. The highest completed education levels were surveyed for the parents. For fathers, 24.3% graduated from 2 year-college or below, 29.3% from 4 year-college, and 45.9% had a graduate degree. For mothers, 8.1% graduated from 2 year-college or below, 29.7 had 4 year-college degree, and 62.1% had a graduate degree. Normal or corrected-to-normal binocular vision (20/40 or better) was confirmed by their performance on a standard Snellen chart.

We note that a portion of participants (n = 17) were intended to participate in a reading remediation program at a reading clinic over the summer. Although recruitment methods were different for this sample (i.e., we asked for reading difficulties in school), we decided to combine all children into one group for the purposes of this study because, a) no formal or informal test was used to confirm the students' reading problems; it was only self-reported by their parents, and b) group comparison was not the focus of this study; we aimed to examine relationships between reader's oral reading fluency and eye tracking measures, hence, grouping by one specific diagnostic measure may not do justice to the heterogeneity in reading skills. To confirm that the distribution of reading problems was not bimodal or skewed, we present Figure 1 (see result section), showing distributions for reading outcomes for the five component reading skills as well as tests confirming normality. Additionally, we found that those 17 children did not differ on key demographic variables such as age (p = .10), gender (p = .46), SES (p = .48), and ethnicity (p = .30) from the remaining children in the sample. The study was approved by the Institutional Review Board at a large research institution from a southwestern state in the United States (IRB2017-0007D).

Reading Skill Measures

Sight Word and Nonword Reading

We used the Sight Word Efficiency and Phoneme Decoding Efficiency subtests of the Test of Word Reading Efficiency (TOWRE; Torgesen, Rashotte, & Wagner, 1999) as indicators of children's decoding skills. While being tested, children were asked to read as many words as they can from a non-word list in 45 seconds. Torgesen et al. reported the test-retest reliability of the TOWRE to be >.90.

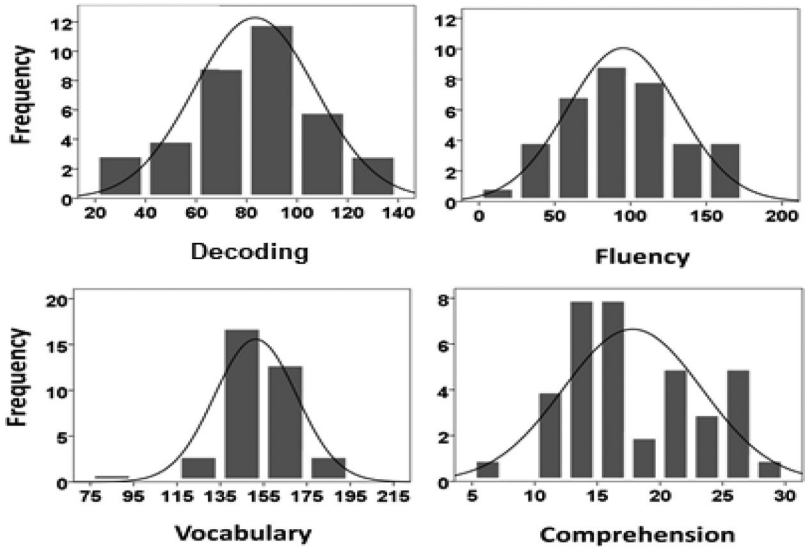

Figure 1. Distributions of decoding, fluency, and reading comprehension.
Note. Decoding score was calculated by summing sight word reading and nonword reading.

Oral Reading Fluency

Oral reading fluency was assessed by the Dynamic Indicators of Basic Early Literacy Skills (DIBELS 6th ed; Good, Kaminski, & Dill, 2007). During the task, the child was asked to read three passages aloud for one minute each. The score was obtained by calculating the number of words that were correctly read in one minute. Omission, substitution, or hesitation for over 3 seconds was scored as an error. Following the DIBELS manual, the median score from the three passages was chosen as the final score (Good et al., 2004). Test-retest reliabilities for elementary students ranged from .92 to .97 (Good et al., 2004). No normed scores were available for this measure.

Vocabulary

Children's receptive vocabulary knowledge was measured using the Peabody Picture Vocabulary Test (PPVT-III; Dunn & Dunn, 1997). In the task, children were asked to select the one picture named by the examiner from four; children are given four pictures and select the one that the examiner verbally named. The median split-half reliability was reported to be .80 and the test-retest reliability to be .92 (Kim, Petscher, Schatschneider, & Foorman, 2010).

Reading Comprehension

Reading comprehension was assessed by the passage comprehension subtest of the Woodcock Reading Mastery Test – III (WRMT-III; Woodcock, 2011). This widely used measure employs a cloze task where children are asked to read short sentences and identify missing keywords for blanks. The reliability for this task was reported as .90 (Simmons et al., 2008).

Eye Tracking Materials

The silent sentence reading task in the present study was adapted from Ashby, Dix, Bontrager, Dey, and Archer (2013). Participants were instructed to read eight sentences (Appendix A) and told that they would be asked to answer a simple comprehension question (yes or no) for each sentence. After a fixation prompt, a sentence would appear on the screen one at a time on a single line, with a maximum of 26 characters using a 30-point Times New Roman font. A character of text would fill 1.0 degree of visual angle. The accuracy rate of responses to comprehension questions was high (92% of total questions were answered correctly) suggesting the children were actually reading and being engaged with the task.

Eye Tracking Measures

We used both word-based and sentence-based eye tracking measures that are widely used in reading research. The word-based measures include first fixation duration, gaze duration, regression path duration, total duration, and word skipping. The sentence-based measures include fixation count and regression frequency. In eye tracking research, these measures have been fine-grained to represent different cognitive processes in reading. For example, first fixation duration, gaze duration and skipping are known to represent early process of reading while regression path duration, total duration and regression frequency are thought to reflect relatively late process of reading.

In the present study, first fixation duration was defined as the initial fixation duration on each word. Gaze duration was defined as the sum of all fixation durations on a word in the first pass and calculated by summing all fixation durations on a word before leaving the word for the first time (Rayner, 1998; Rayner, Slattery, Drieghe, & Liversedge, 2011). Regression path duration was defined as the sum of all fixations beginning with the initial fixation on a word and ending when gaze is directed away from the word to the right. Total

duration was defined as the sum of all fixations on a word. Skipping was defined as the likelihood that a word is skipped during the first time it is encountered and initially produced as binominal value (0 = read, 1 = skipped).

In sentence level analyses, fixation counts were obtained by counting the number of all fixations on a sentence while regression frequency was obtained by summing the number of regressions in a sentence. Note that we only counted the number of inter-word regressions (i.e., regressive saccades across words). Intra-word regressions (i.e., regressive saccades within a word) were not included because they are often caused by readers' corrections of oculomotor targeting errors rather than cognitive reading processes (Inhoff, Kim, & Radach, 2019).

Procedure

All children in the present study were accompanied by a parent to visit the lab so that parent consent and minor assent were obtained. After a brief test of eyesight, the lab visit was roughly composed of four phases: questionnaires, electroencephalography (EEG), eye tracking, and reading behavior. During the first 'questionnaire phase', a parent filled out survey questionnaires regarding their own and their child's perceived reading ability, motivation, and several demographics in a waiting room. The child completed self-report questionnaires and was then being prepared for the EEG (~ 30 minutes). The 'EEG phase' consisted of a baseline (Woltering, Jung, Liu, & Tannock, 2012), a Go-Nogo (Woltering, Liu, Rokeach, & Tannock, 2013), and a word-reading task (~ 60 minutes; data not reported in this manuscript) after which they completed the 'eye tracking phase' (~ 30 minutes; detailed descriptions below). Finally, the child completed the 'reading phase' consisting of various reading tasks (45 to 60 minutes, detailed descriptions below).

During the eye tracking phase, participants were seated in front of a 22-inch widescreen monitor (resolution 1920 × 1080 [24 bits per pixel]; refresh rate 60 Hz) with a viewing distance of approximately 80 cm between the monitor and the participant's eyes. To minimize head movement and standardize the viewing distance, participants were asked to use an adjustable chin rest and a forehead bar. Data was collected using SR Research EyeLink 1000 system (SR Research Ltd., Ontario, Canada) with a sampling rate of 1000 Hz from the right eye. The calibration and validation were deemed successful when an average error was less than 1° and a maximum error was less than 1.5° as tested using a 9-point calibration. During the experiment, the calibration and validation were repeated after any breaks or whenever the experimenter considered it necessary.

To minimize the effects of fatigue and boredom, children took breaks between the phases. Furthermore, after the completion of a phase, children could choose a sticker to be placed on a certificate they would take home as a prize. Children also indicated themselves when they were ready to start a new phase. Though anecdotal and subjective, research assistants typically reported the children to be engaged and alert throughout the entire course of the visit. Families received a 30-dollar-gift card for completion of all sessions. For the purposes of the present study, we mainly focused on data from eye tracking and reading skill measures.

Data Preparation

After data collection, data files were prepared for analyses. Eye tracking data from four participants was immediately removed due to poor validation. Through visual inspection of the eye tracking data (see, Holmqvist et al., 2011; Rau et al., 2016; Vorstius, Radach, & Lonigan, 2014), we determined to remove one additional participant from all following analyses because the child attended to the screen for less than 50% of the time. The visual inspection also revealed that ten participants had trials that needed to be removed for unsatisfactory data quality (e.g., an average of 2.4 trials were removed due to track loss or not reading). We note that because our fixation prompt was centered, children were inadvertently prompted to gaze at the center of the screen and we had to manually remove one or two initial fixations within a trial if those fixations occurred in the middle but then returned to the beginning of the sentence. Further, we removed trials if the first fixation started in the middle of the sentence and moved toward the end. This was the case for 8 participants for an average of 1.75 trials. Finally, the average number of trials for participants was 7 (SD = 1.82, Median = 8, Range = 2-8).

Following standard procedures of eye tracking data, fixation points shorter than 80 ms or longer than 1,000ms were excluded for analyses. However, when fixations shorter than 80 ms had a neighboring larger fixation that was closer than 0.5-degree distance along the x-axis, they were integrated into the neighboring fixation. AOI were defined for each word separately and approximately three times taller than the characters to capture fixations that fell slightly out of text areas. Fixations that fell outside of the AOI were removed. Additionally, an examination of comprehension outcomes for sentences revealed that the number of incorrect answers were negligible. Therefore, it was not included in the following analyses.

Analytic Approach

The analysis plan was determined *a priori*. Before analyses, outliers were Winsorized to 2.5 standard deviation values (see, Tabachnick & Fidell, 2007). Fewer than 1% of the eye-movement data and fewer than 0.5% of the reading skill data needed to be Winsorized. Correlations analyses were conducted to investigate relationships among reading measures (i.e., DIBELS, TOWRE, and WRMT-III) and eye movement measures. To conduct correlation analysis, data points in eye movement measures are averaged to represent each subject.

To examine the research question (i.e., relationship between reading skills and eye tracking measures), we used *R* and *lme4* package to perform linear mixed-effects analyses (Baayen, 2008, Bates, Mächler, Bolker, & Walker, 2015). Linear mixed-effects models are well-established in eye tracking reading studies (Hohenstein, Matuschek, & Kliegl, 2017). In eye tracking studies, participants read multiple sentences or texts yielding many repeated data points. Linear mixed-effects models allow researcher to avoid averaging those data points by modeling the random effects from the variability between subjects and items. The duration measures (i.e., first fixation duration, gaze duration, regression path duration, rereading duration, and total duration) were analyzed using linear mixed-effects models and the frequency measure (i.e., skipping, fixation count, regression frequency) was analyzed with a logit-linear mixed-effects model. We conducted separate linear mixed-effects analyses with eye tracking measures as dependent variables and each of reading skills as an independent variable. All of the models tested included participant and item as random-effects. We used likelihood ratio tests to obtain p values by comparing the full model with the effect in question against the model without the effect in question. Alpha was set at .05 level. Bonferroni corrections were applied on the model fit statistics (criterion shift to: $p < .01$).

Results

Descriptive Statistics and Preliminary Analyses

Table 1 shows the means, standard deviation, and range of the scores for the five reading domains: sight word reading, nonword reading, oral reading fluency, vocabulary and reading comprehension. The following proportions of our sample were categorized as below average or lower in those measures which provide standardized scores: 27% in comprehension (WRMT-III), 21.6% in vocabulary (PPVT-III), and 46% in decoding (TOWRE). As can be seen from Figure 1, the distributions of the four reading component scores appeared to follow a normal

distribution. This was also confirmed by Shapiro-Wilk tests for normality (all p's > .05).

Table 2 summarizes means and SDs, and range of eye movement measures such as first fixation duration, gaze duration, regression path duration, total duration, and skipping probability, fixation count on a sentence, and frequency of inter-word regression.

Table 1. Scores and SDs for Reading Skills and Working Memory.

Reading skills	Mean	SD	Min	Max
Sight Word Reading	57.91	14.84	23	88
Sight Word Reading (SS)	94.95	16.70	65	131
Nonword Reading	23.89	10.90	3	49
Nonword Reading (SS)	89.77	13.63	35	60
Oral Reading Fluency	92.89	36.35	23	172
Vocabulary	149.91	14.46	104	175
Vocabulary (SS)	106.06	15.312	54	144
Reading Comprehension	17.31	5.29	6	28
Reading Comprehension (SS)	99.49	18.79	58	136

Note. SS: Standardized score.

Table 2. Means and SDs for Eye-Movement Measures by Subject.

Eye-movement measure	Mean	SD	Min	Max
First fixation duration (ms)	301	46	212	407
Gaze duration (ms)	421	87	308	700
Regression path duration (ms)	1472	517	546	2750
Total duration (ms)	748	218	370	1293
Skipping probability (%)	.24	.09	.06	.49
Mean fixation count (sentence)	19.1	5.9	10.5	40.5
Interword regression (sentence)	3.24	1.64	1.75	5.00

Note. Skipping probability was calculated by dividing the number of skipped words by total number of words.

Table 3. Correlation Matrix Among Working Memory, Reading Skills, and Eye Movement Variables.

	SWR	NWR	ORF	VOC	COM	FFD	GD	RPD	TD	FC	SKIP
SWR	–										
NWR	.68***	–									
ORF	.86***	.63***	–								
VOC	.24	.17	.26	–							
COM	.64***	.44**	.74***	.54***	–						
FFD	- .42**	-.25	-.44**	-.05	-.34*	–					
GD	- .72***	-.37*	-.69***	-.06	-.53**	.76***	–				
RPD	- .52**	-.45**	-.62***	-.16	-.36*	.15	.31	–			
TD	- .62***	-.50**	-.73***	-.18	-.48**	.34*	.54***	.94***	–		
FC	- .50**	-.39*	-.59***	-.03	-.33	0	.37*	.79***	.84***	–	
SKIP	.37*	.34*	.50**	.06	.45**	-.39*	-.56***	-.08	-.38*	-.44**	–

Note. SWR = sight word reading, NWR = nonword reading, ORF = oral reading fluency, VOC = vocabulary, COM = reading comprehension, FFD = first fixation duration, GD = gaze duration, RPD = regression path duration, TD = total duration, FC = fixation count (sentence), SKP = skipping rate

*p < .05, ** p < .01.

Table 3 depicts the correlations between the reading skills and the eye tracking measures. We note that all eye tracking measures except skipping rate were negatively correlated with sight word reading, nonword reading, oral reading fluency, and comprehension, suggesting that shorter durations were associated with better performances in such measures. In contrast, high and positive correlations were found for skipping with the reading skills measures, suggesting that higher skipping rate was associated with better performances in such measures. It should be noted that vocabulary was not associated with any eye tracking measures.

Associations between Reading Skills and Eye Movements

To examine the associations among reading skills and the eye movement measures, separate linear effects analyses were conducted. The results for the seven eye tracking measures are presented in Table 4. Note that all statistical significances were evaluated with the Bonferroni correction ($^{*}p < .01$, $^{**}p < .002$, $^{***}p < .0002$).

Sight word reading significantly predicted first fixation duration ($b = -1.343$, $p = .0041$), gaze duration ($b = -3.717$, $p < .0002$), regression path duration ($b = -7.618$, $p = .0007$), and total duration ($b = -6.841$, $p = .0002$). Similarly, nonword reading significantly predicted gaze duration, regression path duration, and total duration. The results suggest that children with higher sight word reading or nonword reading skills tend to spend less time on words. It should be noted that sight word reading is more strongly associated with eye movement measures than nonword reading.

Oral reading fluency predicted most of the eye tracking measures except for regression frequency. Main fixed effects were found for oral reading fluency on first fixation duration, gaze duration, regression path duration, total duration, skipping, and fixation count. The result suggests that children with higher oral reading fluency have shorter early and late fixation durations as well as less fixation counts. Additionally, those with higher oral reading skills skipped words more frequently.

Reading comprehension significantly predicted gaze duration, regression path duration, total duration, and skipping rate. Children with higher reading comprehension skill tend to spend less time on fixating words (except, first fixation duration) while skipping words more frequently.

Discussion

The purpose of the present study was to investigate if, and to what extent, reading skills are associated with eye tracking measures in

Table 4. Results on the Mixed-Effects Regressions.

	Fixed effects	*b*	*t/z*	*p*
First Fixation Duration	Sight Word Reading	− 1.343*	− 2.961	.0041
	Nonword Reading	− 1.051	− 1.608	.1045
	Oral Reading Fluency	− .660**	− 3.808	.0004
	Vocabulary	− .248	− .550	.5710
	Reading Comprehension	− 2.938	− 2.271	.0242
Gaze Duration	Sight Word Reading	− 3.717***	− 6.182	< .0002
	Nonword Reading	− 2.847*	− 2.733	.0085
	Oral Reading Fluency	− 1.567***	− 6.828	< .0002
	Vocabulary	− .498	− .645	.5039
	Reading Comprehension	− 7.702**	3.940	.0003
Regression Path Duration	Sight Word Reading	− 7.618**	− 3.599	.0007
	Nonword Reading	− 7.969*	− 2.714	.0084
	Oral Reading Fluency	− 3.491***	− 4.143	< .0002
	Vocabulary	− 2.888	− 1.357	.1797
	Reading Comprehension	− 16.501*	− 2.752	.0078
Total Duration	Sight Word Reading	− 6.841**	− 3.971	.0002
	Nonword Reading	− 7.607*	− 3.132	.0027
	Oral Reading Fluency	− 3.437***	− 5.514	< .0002
	Vocabulary	− 2.410	− 1.368	.1712
	Reading Comprehension	− 16.730**	− 3.470	.0011
Skipping	Sight Word Reading	.003	2.197	.0297
	Nonword Reading	.003	2.300	.0237
	Oral Reading Fluency	001**	3.309	.0017
	Vocabulary	0	.349	.7124
	Reading Comprehension	.008*	2.835	.0064
Fixation Count on a Sentence	Sight Word Reading	− .014	− 2.495	.0139
	Nonword Reading	− .177	− 2.426	.0175
	Oral Reading Fluency	− .073**	− 3.399	.0011
	Vocabulary	− .027	− .526	.5902
	Reading Comprehension	− .311	− 2.022	.0455
Regression Frequency	Sight Word Reading	− .001	− .116	.9036
	Nonword Reading	− .013	.996	.3118
	Oral Reading Fluency	− .002	− .413	.6744
	Vocabulary	0	.016	.9886
	Reading Comprehension	− .004	− .132	.8917

*$p < .01$, **$p < .002$, ***$p < .0002$ (Bonferroni Correction).

elementary school students. Overall, we found evidence that reading skills could reliably predict various eye tracking measures.

Our findings show that elementary children's reading skills reliably predicted their eye movement behaviors. These findings are largely

consistent with those in the published literature. Studies have found that low word reading proficiency was related to increased rereading time of text in Grade 2 children (Kim, Vorstius, & Radach, 2018) and longer gaze duration (Barnes, Kim, Tighe, & Vorstius, 2017; De Leeuw, Segers, & Verhoeven, 2016b; Kuperman & Van Dyke, 2011). Barnes et al. also reported that passage comprehension was negatively related to gaze duration. Therefore, it seems that eye tracking measures, regardless of early or late processing measures, reflect both low-level reading processes (i.e., sight word reading, nonword reading, reading fluency) and higher-level reading process (i.e., reading comprehension).

In our study, we also divided our eye tracking measures into duration and frequency measures. An interesting pattern emerged, in which the duration measures seemed to have ubiquitous and strong effects across the different domains of reading. That is, duration measures were associated with most of the reading skills while frequency measures tended not to be predicted by or weakly associated with the reading skills. One possible explanation for this finding is that several of our reading skill measures were conducted under time-constraints (e.g., the TOWRE-II and DIBELS), which may have made them more sensitive to duration eye movement measures also related to processing time. Another possibility is that frequency measures such as skipping and regression are more advanced reading abilities that elementary graders have not fully developed. For instance, according to Häikiö, Bertram, Hyönä, and Niemi (2009), effective parafoveal processing only becomes fully adult-like in Grade 6. Hence, there would be a limitation for earlier grade children to successfully extract information from upcoming words in order to plan their next saccadic eye movements.

We found strong associations between oral reading fluency and eye tracking measures which replicate previous findings in the literature. For example, Zawoyski and Ardoin (2019) found negative correlations between oral reading fluency and first fixation duration, gaze duration, total duration, and fixation count. One extended finding of the present study is that oral reading fluency was indicative of word skipping. More fluency readers skipped more words in the silent sentence reading. This may suggest fast and accurate oral reading and skipping behaviors in silent sentence reading share the same underlying cognitive processes. However, this result may need to be interpreted with caution because skipping could occur fixation errors (Inhoff et al., 2019).

Additionally, we found no significant relation between vocabulary and any of the eye tracking measures. This was inconsistent with a previous study in which low vocabulary knowledge related to longer gaze duration in a sample of Dutch primary school students (De Leeuw, Segers, & Verhoeven, 2016b). We assume that this inconsistency might be due to

the difference of reading tasks for eye tracking. In the abovementioned study, the researchers used newspaper articles composed of multiple paragraphs while we employed short single-line sentences. To the best of our knowledge, no other studies have examined the relation between vocabulary knowledge and eye tracking measures, and thus, we recommend the need to further examine this topic in future studies.

Implications of the Study

The present study extends the scope of the existing research by including a comprehensive set of reading skills. Additionally, we used linear fixed effect models to analyze data in word level, avoiding averaging of repeated data points. Our findings may also have practical implications as they can be a first step in finding supportive measures to diagnose reading problems in children. Because eye tracking provides extensive moment-to-moment data, they have the potential to provide more precise information about what kind of cognitive processes are impaired in children with reading problems. As such, eye tracking measures have the potential to provide unique diagnostic information. For example, the patterns of students' eye movement reflected on first fixation duration, gaze duration, regression path duration, total duration, and skipping would collectively indicate their reading fluency skills. Specifically, low skipping rate and longer fixation durations in words might generally suggest fluency problems in children.

Limitations and Future Directions

Several limitations of this study need to be mentioned. First, we had relatively small sample (n = 35). This may impact the generalizability of the findings of the study. Though we acknowledge the small sample size of our study, we note that this is comparable with other eye tracking research in pediatric samples published to date.

Second, our sample consisted largely of families coming from high SES and education levels which limits the generalization of our study. Further, as mentioned, we used different recruitment methods that made the sample heterogeneous. Therefore, future studies may need to confirm the results of the present study using a larger sample of participants with a more diverse demographic profile.

Third, there was also heterogeneity in age (7-10) and grade levels (1-4) which precluded statements about developmental progressions. However, our aim was not examining developmental pathways of eye movements or reading skills but exploring the relationship between them in elementary grade children.

Finally, even though the measurements we used in the study have been widely-used in the field of literacy research, they might not be

the most representative instruments for those target reading skills. We acknowledge that researchers might obtain different results by using other measures. This also suggests another important direction of future studies.

Conclusion

Reading is a multidimensional activity that includes various cognitive processes. In the present study, we examined the relationship between eye tracking measures and different component reading skills. We found that the variance of several component reading skills such as decoding, fluency, and comprehension were explained by eye tracking measures. As mentioned, our study is exploratory in nature. The results of the study need to be further confirmed by future studies.

ORCID

Sungyoon Lee http://orcid.org/0000-0002-3326-1966
Qinxin Shi http://orcid.org/0000-0003-2157-0590
Huilin Sun http://orcid.org/0000-0003-4132-0337
Julie L. Thompson http://orcid.org/0000-0002-2361-1707

References

Alexander, P. A., & Fox, E. (2008). Reading in perspective. In M. J. Fresch (Ed.), *An essential history of current reading practices* (pp. 12–32). Newark, DE: International Reading Association.

Ashby, J., Dix, H., Bontrager, M., Dey, R., & Archer, A. (2013). Phonemic awareness contributes to text reading fluency: Evidence from eye movements. *School Psychology Review*, *42*(2), 157–170. doi:10.1080/02796015.2013.12087482

Baayen, R. H. (2008). *Analyzing linguistic data: A practical introduction to statistics using R*. Cambridge, UK: Cambridge University Press.

Barnes, A. E., & Kim, Y. S. (2016). Low-skilled adult readers look like typically developing child readers: A comparison of reading skills and eye movement behavior. *Reading and Writing*, *29*(9), 1889–1914. doi:10.1007/s11145-016-9657-5

Barnes, A. E., Kim, Y. S., Tighe, E. L., & Vorstius, C. (2017). Readers in adult basic education: Component skills, eye movements, and fluency. *Journal of Learning Disabilities*, *50*(2), 180–194.

Bates, D., Mächler, M., Bolker, B., & Walker, S. (2015). Fitting linear mixed-effects models using lme4. *Journal of Statistical Software, 67*(1), 1–48. doi:10.18637/jss.v067.i01

Brysbaert, M., Drieghe, D., & Vitu, F. (2005). Word skipping: Implications for theories of eye movement control in reading. In G. Underwood (Ed.), *Cognitive processes in eye guidance* (pp. 53–78). New York, NY: Oxford University Press.

Conklin, K., & Pellicer-Sánchez, A. (2016). Using eye-tracking in applied linguistics and second language research. *Second Language Research*, *32*(3), 453–467. doi:10.1177/0267658316637401

De Leeuw, L., Segers, E., & Verhoeven, L. (2016a). Role of text and student characteristics in real-time reading processes across the primary grades. *Journal of Research in Reading*, *39*(4), 389–408. doi:10.1111/1467-9817.12054

De Leeuw, L., Segers, E., & Verhoeven, L. (2016b). The effect of student-related and text-related characteristics on student's reading behaviour and text comprehension: An eye movement study. *Scientific Studies of Reading*, *20*(3), 248–263. doi:10.1080/10888438.2016.1146285

Dunn, L. M., & Dunn, L. M. (1997). *PPVT-III: Peabody picture vocabulary test*. Circle Pines, MN: American Guidance Service.

Foster, T. E., Ardoin, S. P., & Binder, K. S. (2018). Reliability and validity of eye movement measures of children's reading. *Reading Research Quarterly*, *53*(1), 71–89. doi:10.1002/rrq.182

Good, R. H., Kaminski, R. A., & Dill, S. (2007). DIBELS oral reading fluency. In R. H. Good & R. A. Kaminski (Eds.), *Dynamic indicators of basic early literacy skills* (6th ed.). Eugene, OR: Institute for the Development of Educational Achievement.

Good, R.H., Kaminski, R.A., Shinn, M., Bratten, J., Shinn, M., Laimon, D., … Flindt, N. (2004). *Technical adequacy of DIBELS: Results of the early childhood research institute on measuring growth and development (Technical Report, No. 7)*. University of Oregon.

Häikiö, T., Bertram, R., Hyönä, J., & Niemi, P. (2009). Development of the letter identity span in reading: Evidence from the eye movement moving window paradigm. *Journal of Experimental Child Psychology*, *102*(2), 167–181. doi:10.1016/j.jecp.2008.04.002

Hohenstein, S., Matuschek, H., & Kliegl, R. (2017). Linked linear mixed models: A joint analysis of fixation locations and fixation durations in natural reading. *Psychonomic Bulletin & Review*, *24*(3), 637–651. doi:10.3758/s13423-016-1138-y

Holmqvist, K., Nyström, M., Andersson, R., Dewhurst, R., Jarodzka, H., & Van de Weijer, J. (2011). *Eye tracking: A comprehensive guide to methods and measures*. New York, NY: Oxford University Press.

Huck, A., Thompson, R. L., Cruice, M., & Marshall, J. (2017). Effects of word frequency and contextual predictability on sentence reading in aphasia: An eye movement analysis. *Aphasiology*, *31*(11), 1307–1332. doi:10.1080/02687038.2017.1278741

Inhoff, A. W., Kim, A., & Radach, R. (2019). Regressions during reading. *Vision*, *3*(3), 35. doi:10.3390/vision3030035

Kim, Y. S., Petscher, Y., Schatschneider, C., & Foorman, B. (2010). Does growth rate in oral reading fluency matter in predicting reading comprehension achievement? *Journal of Educational Psychology*, *102*(3), 652–667. doi:10.1037/a0019643

Kim, Y. S. G., Vorstius, C., & Radach, R. (2018). Does online comprehension monitoring make a unique contribution to reading comprehension in beginning readers? Evidence from eye movements. *Scientific Studies of Reading : The Official Journal of the Society for the Scientific Study of Reading*, *22*(5), 367–383. doi:10.1080/10888438.2018.1457680

Kirby, J.R. (2007). Reading comprehension: Its nature and development. In *Encyclopedia of language and literacy development* (pp. 1–8). London: Canadian Language and Literacy Research Network. http://www.literacyencyclopedia.ca/index.php?fa=items.show&topicID=227.

Kuperman, V., & Van Dyke, J. A. (2011). Effects of individual differences in verbal skills on eye-movement patterns during sentence reading. *Journal of Memory and Language*, *65*(1), 42–73. doi:10.1016/j.jml.2011.03.002

National Reading Panel. (2000). *Report of the national reading panel. Teaching children to read: An evidence-based assessment of the scientific research literature on reading and its implications for reading instructions (NIH Publication No. 00-4769)*. U.S. Government Printing Office.

Nicol, J., Swinney, D., Love, T., & Hald, L. (2006). The on-line study of sentence comprehension: An examination of dual task paradigms. *Journal of Psycholinguistic Research*, *35*(3), 215–231.

Raney, G. E., Campbell, S. J., & Bovee, J. C. (2014). Using eye movements to evaluate the cognitive processes involved in text comprehension. *Journal of Visualized Experiments*, *83*(83), e50780. doi:10.3791/50780

Rau, A. K., Moll, K., Moeller, K., Huber, S., Snowling, M. J., & Landerl, K. (2016). Same same, but different: Word and sentence reading in German and English. *Scientific Studies of Reading*, *20*(3), 203–219. doi:10.1080/10888438.2015.1136913

Rayner, K. (1998). Eye movements in reading and information processing: 20 years of research. *Psychological Bulletin*, *124*(3), 372–422. doi:10.1037/0033-2909.124.3.372

Rayner, K., Pollatsek, A., Ashby, J., & Clifton, C.Jr, (2012). *Psychology of reading* (2nd ed.). New York, NY: Psychology Press.

Rayner, K., Slattery, T. J., Drieghe, D., & Liversedge, S. P. (2011). Eye movements and word skipping during reading: Effects of word length and predictability. *Journal of Experimental Psychology. Human Perception and Performance*, *37*(2), 514–528. doi:10.1037/a0020990

Rogers, L. S., & Ardoin, S. P. (2018). Investigating the benefit of adding listening passage preview to repeated readings. *School Psychology Quarterly : The Official Journal of the Division of School Psychology, American Psychological Association*, *33*(3), 439–447.

Schroeder, S., Hyönä, J., & Liversedge, S. P. (2015). Developmental eye-tracking research in reading: Introduction to the special issue. *Journal of Cognitive Psychology*, *27*(5), 500–510. doi:10.1080/20445911.2015.1046877

Simmons, D. C., Coyne, M. D., Kwok, O-m., McDonagh, S., Ham, B. A., & Kame'enui, E. J. (2008). Indexing response to intervention: A longitudinal study of reading risk from kindergarten through third grade. *Journal of Learning Disabilities*, *41*(2), 158–173. doi:10.1177/0022219407313587

Tabachnick, B. G., & Fidell, L. S. (2007). *Experimental design using ANOVA*. Belmont, CA: Duxbury Press.

Torgesen, J. K., Rashotte, C. A., & Wagner, R. K. (1999). *TOWRE: Test of word reading efficiency*. Austin, TX: Pro-ed.

Vorstius, C., Radach, R., & Lonigan, C. J. (2014). Eye movements in developing readers: A comparison of silent and oral sentence reading. *Visual Cognition*, *22*(3-4), 458–485. doi:10.1080/13506285.2014.881445

Woltering, S., Jung, J., Liu, Z., & Tannock, R. (2012). Resting state EEG oscillatory power differences in ADHD college students and their peers. *Behavioral and Brain Functions : BBF*, *8*(60), 60. doi:10.1186/1744-9081-8-60

Woltering, S., Liu, Z., Rokeach, A., & Tannock, R. (2013). Neurophysiological differences in inhibitory control between adults with ADHD and their peers. *Neuropsychologia*, *51*(10), 1888–1895. doi:10.1016/j.neuropsychologia.2013.06.023

Woodcock, R. W. (2011). *Woodcock reading mastery tests* - Third Edition. San Antonio, TX: Pearson.

Zawoyski, A. M., & Ardoin, S. P. (2019). Using eye-tracking technology to examine the impact of question format on reading behavior in elementary students. *School Psychology Review*, *48*(4), 320–332. doi:10.17105/SPR-2018-0014.V48-4

Appendix A: Materials

Sentence Reading and Questions

Dad got a pet for Tom at the mall.	Did he buy it?
Pat had a net to take to the woods.	Did she have the net?
The pig did not swim in the pool.	Did the pig swim?
The tin frog sat in the back yard.	Did the frog jump?
Sue had to catch the dog.	Was the dog in the yard?
The cat hid in a log by the river.	Was the cat in a box?
The bug jumped and stung Tom.	Did the bug sting?
Beth likes her cat named Bob.	Does Beth have a pet?

**Questions were read aloud to the child.

View publication stats