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# Unpacking eye movements during oral and silent reading and their relations to reading proficiency in beginning readers

Young-Suk Grace Kim[a,*], Yaacov Petscher[b], Christian Vorstius[c]

[a] University of California, Irvine, USA
[b] Florida State University and Florida Center for Reading Research, USA
[c] University of Wuppertal, Germany

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ABSTRACT

Our understanding about the developmental similarities and differences between oral and silent reading and their relations to reading proficiency (word reading and reading comprehension) in beginning readers is limited. To fill this gap, we investigated 368 first graders' oral and silent reading using eye-tracking technology at the beginning and end of the school year. Oral reading took a longer time (greater rereading times and refixations) than silent reading, but showed greater development (greater reduction in rereading times and fixations) from the beginning to the end of the year. The relation of eye-movement behaviors to reading proficiency was such that, for example, less rereading time was positively related to reading proficiency, and the relation was stronger in oral reading than in silent reading. Moreover, the nature of relations between eye movements and reading skill varied as a function of the child's reading proficiency such that the relations were weaker for poor readers, particularly at the beginning of the year. The relations between eye movements and reading proficiency stabilized in the spring for children whose reading skill was 0.30 quantile and above, but weaker relations remained for readers below 0.30 quantile. These findings suggest the importance of examining eye-movement behaviors in both oral and silent reading modes and their developmental relations to reading proficiency.

## 1. Introduction

Reading involves complex processes. As such, it has been studied in multiple fields including cognitive psychology, developmental psychology, and education to name a few. Cognitive psychology as a field has provided in-depth information about single-word recognition (McClelland & Rumelhart, 1981; Norris, 2013) as well as online word processing during sentence and passage reading using eye-tracking technology (e.g., Inhoff & Radach, 1998; Rayner, 1998, 2009; Reichle, 2015). The developmental psychology and education fields have typically focused on individual differences in reading, oral language, and cognition and revealed important precursors to reading development (e.g., see Adams, 1990; National Center for Family Literacy, 2009; National Institute of Child Health and Human Development [NICHD], 2000). Overall, different foci and traditions in these various fields have been extremely informative and insightful about complex processes involved in reading from multiple perspectives. One downside, however, is that integration of perspectives across fields does not readily occur. The present study is an effort to bridge and integrate techniques and perspectives from these multiple disciplines to advance our understanding about reading processes[1] for beginning readers. Specifically, we (a) examined online reading processes during oral and silent reading using eye-tracking technology and (b) investigated the relations of eye-movement behaviors to reading proficiency, using longitudinal data from children in Grade 1 (from the beginning to end of the school year).

## 2. Eye movements during reading

### 2.1. Eye movements during reading

Eye movements provide a useful, sensitive window into cognitive processing and, therefore, are ideal for examining developmental changes and processes (Blythe, 2014). In cognitive psychology, reading is regarded as a special case of complex information processing, and eye movements are used to reveal the underlying processes and their coordination (see e.g., Radach & Kennedy, 2013; Rayner, 1998, 2009;

* Corresponding author at: School of Education, University of California, Irvine, 3200 Education Building, Office 3455, Irvine, CA 92697, USA.
*E-mail address:* Young.kim@uci.edu (Y.-S.G. Kim).

[1] 'Reading processes' subsume all cognitive processes that contribute to successfully extracting meaning from written text, ranging from letter and word decoding to higher level integration. Some of these processes are thought to be made available for examination through specific eye-movement measures (see below).

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Reichle, 2015). Understanding eye-movement behavior in reading is related to two critical decisions that are made repeatedly during reading, namely (1) *when* to execute a movement and (2) *where* to move the eyes next (Findlay & Walker, 1999; Radach & Kennedy, 2004; Rayner & McConkie, 1976). In an effort to understand what influences these decisions, various computational reading models have been developed, which combine known mechanisms of oculomotor control and linguistic processing (see the E-Z Reader model by Reichle, Rayner, & Pollatsek, 2003; SWIFT by Engbert, Longtin, & Kliegl, 2002; Glenmore model by Reilly & Radach, 2006; and Oculomotor-based model by Yang, 2006). Although specific details differ, a basic assumption across these models is that certain eye-movement behaviors are associated with specific underlying cognitive processes. For instance, the amount of time spent on a word at first fixation (first fixation duration) is hypothesized to capture initial decoding processes. The amount of time spent refixating a word after initial fixation (refixation time; i.e., immediately making another fixation on the same word as that of the preceding fixation) is believed to capture lexical access (Inhoff, 1984; Inhoff & Radach, 1998; Rayner & Pollatsek, 1987), and further rereading of a word (rereading time; i.e., coming back to the word after having read one or multiple other words) is believed to be an indicator of higher order syntactic integration processes (Frazier & Rayner, 1982; Radach, Huestegge, & Reilly, 2008; Radach & Kennedy, 2004; Rayner, Chace, Slattery, & Ashby, 2006; but see Kliegl & Laubrock, 2017, for a dynamic view).

In order to adequately describe eye-movement behaviors during reading, a number of measures are widely used. These include temporal measures (e.g., amount of time spent looking at a word), count/proportion measures (e.g., number of fixations and gazes, proportions of refixations and regressions), and spatial measures (e.g., how far the eyes move in a saccade and initial landing position within a word). With regard to temporal measures, on average, proficient adult readers in silent reading spend approximately 200–250 ms during first fixation on a word, independent of whether the word will receive any other fixations or not; an additional 100–120 ms when refixating on the same word; and approximately 200–220 ms when rereading the same word (Radach et al., 2008; Rayner, 1998). Furthermore, about 15% of saccades are regressions, which means that one to two out of 10 saccades move the eyes against the reading direction, back to material already read (Rayner, 1998). Finally, spatial measures provide information about where information is extracted during reading (Rayner, 1998). For proficient adult readers, saccades in silent reading are six to eight letters and the initial landing position is about halfway between the beginning and the middle of a word (McConkie, Kerr, Reddix, & Zola, 1988; McConkie, Kerr, Reddix, Zola, & Jacobs, 1989; O'Regan, 1981; Radach & Kempe, 1993; Rayner, Fischer, & Pollatsek, 1998). Models of eye movements in reading as mentioned above (e.g., E-Z reader) can adequately reproduce reading behavior found in proficient *adult* readers, replicating well established effects such that familiar words, shorter words, and frequently occurring words are fixated for a shorter time (e.g., Clifton, Staub, & Rayner, 2007; Inhoff, 1984; Inhoff & Rayner, 1986; Rayner & Duffy, 1986; Reichle et al., 2003) and are skipped more often (e.g., Brysbaert, Drieghe, & Vitu, 2005; White, 2007). A good example that different temporal eye movement measures can indeed represent different online processes is Radach, Schmitten, Glover, and Huestegge (2008) study, showing specific effects of word length, reading mode (oral vs. silent), and language on refixation and rereading times.

### *2.2. Eye movements for beginning readers*

Previous work on eye movements has revealed rich information about cognitive processes involved in the complex mental task of reading in proficient *adult* readers. In the present study, we focus on *children's* eye movements and their relations to reading proficiency. Although research on children's eye movements has gained some momentum over the last decade (Blythe & Joseph, 2011; Blythe, 2014; Henry, Van Dyke, & Kuperman, 2018; Pan, Yan, Laubrock, Shu, & Kliegl, 2013; Sperlich, Meixner, & Laubrock, 2016; Sperlich, Schad, & Laubrock, 2015; Vorstius, Radach, Mayer, & Lonigan, 2013; Vorstius, Radach, & Lonigan, 2014; Yan, Pan, Laubrock, Kliegl, & Shu, 2013), our understanding of eye movements for developing readers is still highly limited. This is a critical gap in the literature because data from developing readers can reveal developmental changes associated with reading *acquisition*. For example, although limited, there is some evidence of similarities and differences between adult readers and developing readers. Like adult proficient readers, developing readers fixate high frequency words for a shorter duration than low frequency words. Compared to adult readers, however, children's perceptual span is smaller, particularly for beginning and poor readers, which results in extraction of less information from the parafovea, at least until the age of 11 to 12 years (Häikiö, Bertram, & Hyönä, 2010; Rayner, 1986). Similar findings were also reported with cross-sectional and longitudinal data on German beginning readers (2016; Sperlich et al., 2015). Combining cognitive-process measures (eye tracking) with individual-difference assessments (off-line assessments of reading performance), Sperlich et al. concluded that the efficient use of parafoveal information presupposes that basic processes of reading have been mastered, which happens around second grade in the German sample. Other studies showed that time spent fixating on words (first fixation duration and refixation time) and proportion of rereading words decreased across Grades 1 to 5. Prolonged reading time was particularly the case for those with weaker reading comprehension skills (Vorstius et al., 2014).

These findings are overall in line with developmental models of word reading. According to the developmental theories of word recognition, children undergo a certain sequence in word reading development (Ehri, 2005; LaBerge & Samuels, 1974; Perfetti, 1992, 2007; Seymour & Duncan, 2001) such that decoding or word reading develops from slow and laborious small-unit based reading (e.g., letter-by-letter reading), as children establish connections among orthography, phonology, and semantics, to automatized, unitary, and fully specified representation of individual words. As beginning readers are actively establishing connections among orthography, phonology, and semantics, decoding processes act as a bottleneck to a large extent, particularly during the beginning phase of reading development. Therefore, there is a critical difference between proficient reading and developmental reading in the extent to which decoding processes constrain cognitive processes.

### *2.3. Oral versus silent reading for children*

Silent reading is the primary mode of reading for proficient readers, and proficient readers typically read faster in silent than oral mode (Rayner, 1998). During the *acquisition* of reading, though, children start with oral reading before transitioning to silent reading (Hiebert & Reutzel, 2010). Oral reading involves more ongoing processes than silent reading does, as overt language production (sounding out words, intonation, etc.) has to be integrated with ongoing language perception. The need for coordination of the receptive and productive processing streams is evident in the eye-voice span (Inhoff, Solomon, Radach, & Seymour, 2011; Laubrock & Kliegl, 2015; Pan et al., 2013; Yan et al., 2013), which is larger when dealing with easy text compared to more difficult text. When it comes to the relation of reading mode to reading comprehension, conflicting views are found in the literature: Some studies found that oral reading enhances comprehension (Fuchs & Maxwell, 1988; Kragler, 1995; Miller & Smith, 1990; Prior & Welling, 2001; Swalm, 1973) due to benefits from the additional auditory input whereas other studies indicated that oral reading has disruptive effects due to the devotion of extra resources to pronunciation, intonation, and monitoring (Jones & Lockhart, 1919). Alternatively, Juel and Holmes (1981) suggested that the effect of reading mode on comprehension depends on the phase of reading development. Whereas beginning and struggling readers show better comprehension during oral reading, readers in higher grades (3rd and 4th) show no difference in comprehension between reading modes, and skilled (adult) readers exhibit better comprehension during silent reading.

Although these previous studies are informative, there are several critical questions that remain largely underexplored, including the extent to which oral and silent reading compare, how they change over time, and how eye movements during oral and silent reading relate to reading proficiency for beginning readers. Ongoing, online processes during silent reading have been a challenge to measure. However, with the advancement of eye-tracking technology, we can now precisely examine moment-to-moment, online cognitive processes during both oral and silent reading and compare these processes between the reading modes. In fact, a recent cross-sectional study with elementary grade children showed that eye-movement behaviors differed as a function of oral versus silent reading such that children had more frequent and prolonged fixations and fewer interword regressions in oral reading than in silent reading (Ashby, Yang, Evans, & Rayner, 2012; Vorstius et al., 2014). In the present study, we extend our understanding of oral and silent reading for beginning readers in a couple of important ways. First, we examined eye-movement behaviors during oral and silent reading and their changes in Grade 1 children from the beginning to end of the school year, using longitudinal data, which provide true developmental information. Second, we systematically examined the relations of eye movements during oral reading and silent reading to reading proficiency (as measured by widely used off-line word reading and reading comprehension tasks), again using longitudinal data. Prior work with adults suggested that processes during oral versus silent reading might essentially be the same (e.g., Anderson & Swanson, 1937; Ashby et al., 2012). However, eye movements during silent reading were weakly to moderately related to reading speed and errors during oral reading for sixth graders in Norway (SØvik, Arntzen, & Samuelsteuen, 2000). These prior studies were based on data from adults or older children and/or did not examine the relations of eye movements to reading proficiency using the same measures in oral versus silent reading. In the present study, we investigated how the same eye-movement measures during oral and silent reading are related to reading proficiency at the beginning and end of Grade 1. Given rapid development of reading during Grade 1, the nature of relations might vary between oral and silent reading, and from the beginning to end of the school year.

### 2.4. Individual differences in reading skill and eye movements during reading

When it comes to reading processes, the field of cognitive psychology tends to focus on detailed within-individual processes such as the effects of word and text characteristics, using online eye-movement information (Blythe, Häkiö, Bertram, Liversedge, & Hyönä, 2011; Blythe, Liversedge, Joseph, White, & Rayner, 2009; Huestegge, Radach, Corbic, & Huestegge, 2009; Hyönä & Olson, 1995; Inhoff & Radach, 1998; Joseph, Liversedge, Blythe, White, & Rayner, 2009; Joseph, Nation, & Liversedge, 2013; Radach & Kennedy, 2004; Rayner, 1986; Rayner et al., 2006; Reichle, Rayner, & Pollatsek, 2006; Reilly & Radach, 2006). On the other hand, the field of education largely focuses on individual differences (e.g., in reading proficiency) using off-line tasks (i.e., language, cognitive, and reading tasks). Although potentially complementary, these two fields have been investigating reading processes in principally disparate lines. However, examining both online processes and individual differences *simultaneously* is necessary and important to advance our understanding about reading acquisition (Radach & Kennedy, 2013; see Sperlich et al., 2015, 2016). For instance, according to the Verbal Efficiency Theory (Perfetti, 2007), the triangle model of word reading (e.g., Adams, 1990; Seidenberg & McClelland, 1989), and an associated large body of supporting evidence, individual differences in phonological, semantic, and orthographic processes contribute to word reading proficiency (e.g., Adams, 1990; NICHD, 2000; Vorstius et al., 2013). Furthermore, the theoretical models on the eye-mind link noted above hypothesize a direct link between oculomotor control and linguistic or reading processes. Then, individual differences in reading proficiency should be related to in-the-moment (online) reading processes. That is, on-line processes employed during reading would be influenced by individual differences in reading skills. Surprisingly few studies have examined this question but a few extant studies have provided interesting insights. For example, Ashby, Rayner, and Clifton (2005) investigated skilled and average adult readers during silent reading and found that online word reading processing differed as a function of their reading proficiency. For developing readers, Sperlich et al. (2016) showed in a longitudinal study that lexical decoding efficiency precedes the development of the perceptual span. Kuperman and van Dyke (2011) studied young adults who were non-college-bound and found that rapid automatized naming and word reading skill were associated with eye-movement behaviors such as first- and second-pass reading duration and refixation probability. In addition, recent studies examined eye movements during rapid automatized naming (RAN) for typically developing readers and those with dyslexia (e.g., Henry et al., 2018; Pan et al., 2013; Yan et al., 2013) and found differences in parafoveal processing between these readers. Similarly, better readers and spellers had larger perceptual spans and tended to make more use of parafoveal information compared to lower skilled individuals (Veldre & Andrews, 2014, 2015, 2016).

In the present study, we extend these previous studies by investigating developmental relations between online reading processes (i.e., eye movements) and reading proficiency (as measured by off-line tasks) for beginning readers—how eye movements relate to reading proficiency and whether the relations are similar or different in different reading modes (i.e., oral reading and silent reading) and as a function of children's reading proficiency among beginning readers (i.e., poor versus more advanced beginning readers).

## 3. Present study

The present study is an effort to expand our understanding about online reading processes as measured by eye movements during oral and silent reading, their changes from the fall to spring of Grade 1, and their relations to reading proficiency. First grade is an important period when reading acquisition occurs at a rapid pace, and thus, examining developmental changes using longitudinal data should be revealing. Specific research questions were as follows:

1. What are characteristics of eye-movement behaviors in oral and silent reading and how do they change from the beginning to end of the school year for children in Grade 1?
2. How are eye-movement behaviors related to reading proficiency measured by word reading and reading comprehension? Do the relations differ in oral versus silent reading? Do the relations differ as a function of children's reading proficiency (low word reading proficiency versus higher proficiency) and over time (beginning and end of the school year)?

Children's reading proficiency was measured at the lexical level (i.e., word reading) and at the discourse level (i.e., reading comprehension). Although previous studies have indicated that word reading and reading comprehension are very strongly related at the beginning phase of reading development, both were examined as they are key skills in reading development and draw on different language and cognitive skills and processes as reading skills develop (Kim, 2015, 2017). We anticipated that there would be significant differences in eye movements from fall to spring in both oral and silent reading. Based on prior, albeit limited, studies (e.g., Ashby et al., 2012; Vorstius et al., 2014), we hypothesized that oral reading would take a longer time (i.e., larger values on temporal eye-movement indicators) than would silent reading at the beginning and end of the school year. As for the relations between eye movements and reading proficiency, we expected stronger relations with oral reading than with silent reading, based on a prior study with struggling readers in fourth grade (Fuchs & Maxwell, 1988; Schimmel & Ness, 2017). We did not have a specific hypothesis about

whether relations may differ as a function of children's reading proficiency due to lack of prior work.

## 4. Method

### 4.1. Participants

A total of 368 first-grade children (49% girls; mean age = 6 years 4 months) from six schools in the United States were assessed at the beginning (fall) and end (spring) of the academic year. All children had normal or corrected-to-normal vision. All first graders in the participating schools were invited to participate in the study except for those with severe intellectual disability or emotional or behavioral disabilities identified from school records. Fifty-two percent of students were eligible for free or reduced-price lunch (an indicator of poverty status), and < 1% of students were identified as limited English proficient. Student race was primarily White (60%), followed by Black (26%), Hispanic (6%), Multiracial (6%), and Asian (2%). Approximately 11% of participants were identified as having either speech impairments (8%), language impairments (1%), or other health impairments (2%). Due to missing assessment data, 18 children were excluded from the analytic sample. Further, after accounting for selection criteria regarding eye-movement data (see below), the final analytic data set consisted of 262, 282, 338, and 345 children who completed the fall silent, fall oral, spring silent, and spring oral reading assessments, respectively.

### 4.2. Measures

#### 4.2.1. Reading proficiency (word reading and reading comprehension)

Two tasks were used to measure children's word reading and reading comprehension, respectively, in order to measure these skills with precision (i.e., reduce measurement error; see Cutting & Scarborough, 2006; Keenan, Betjemann, & Olson, 2008 regarding the importance of measuring comprehension with multiple measures). For word reading skill, the Letter Word Identification task of the Woodcock Johnson Tests of Achievement-III (WJ-III; Woodcock, McGrew, & Mather, 2001) and the Word Reading subtest of the Wechsler Individual Achievement Test-Third Edition (WIAT-III; Wechsler, 2009) were used. In these tasks, the child was asked to read aloud a list of words ordered by increasing difficulty. Cronbach's alpha from the present sample was estimated to be 0.91 in both the fall and the spring for WJ-III Letter Word Identification and 0.95 in both the fall and the spring for WIAT-III Word Reading. WJ-III Letter Word Identification and WIAT-III Word Reading are strongly related to each other ($rs \geq 0.90$; Kim & Petscher, 2016) and other word reading tasks (e.g., Kim & Wagner, 2015; Wagner, Torgesen, & Rashotte, 2012).

Reading comprehension skill was measured by the widely used Passage Comprehension subtest of the WJ-III (Woodcock et al., 2001) and the Reading Comprehension subset of the WIAT-III (Wechsler, 2009). In WJ-III Passage Comprehension, the child was asked to read sentences and passages and complete fill-in-the-blank questions. In WIAT-III Reading Comprehension, the child read a passage and was asked multiple choice questions. Cronbach's alpha from the present sample was estimated to be 0.88 in the fall and 0.81 in the spring for WJ-III Passage Comprehension and 0.88 in the fall and 0.86 in the spring for WIAT-III Reading Comprehension. WJ-III Passage Comprehension and WIAT-III Reading Comprehension are strongly related to each other (Kim & Petscher, 2016) and are moderately to strongly related to other measures of reading comprehension (e.g., PIAT reading comprehension; Keenan et al., 2008).

#### 4.2.2. Eye movements during reading

To assess children's eye movements during reading, children read a number of short passages. These passages were originally developed and normed for children in Grade 1 in a state where the study was conducted (Florida Department of Education, 2009). Three passages were presented to each child at each assessment point, fall and spring, with a total of five different passages across fall and spring because one passage was administered at both times. This linking passage was included to allow for more in-depth comparisons between time points, though such comparisons are beyond the scope of this paper. Passages ranged from 151 to 198 words in length and from 400 to 700 in lexile score (a measure of text difficulty; see Fitzgerald et al., 2015; Stenner, Burdick, Sanford, & Burdick, 2006, for further information). The same passages were used for both oral reading and silent reading sessions within each assessment wave. Oral and silent reading sessions within each assessment wave were, on average, one week apart, and the order of oral and silent reading sessions was counterbalanced across children. Passages were presented on a computer monitor, and children were asked to read the texts aloud in the oral reading session and silently in the silent reading session. To ensure that children read the passages for meaning or comprehension rather than for speed, one literal comprehension question (correct answer is explicitly provided in the given text; e.g., name of a character in the passage) was asked after each passage and answers were digitally recorded using digital recorders such as Olympus VN 8100 pc. These questions were designed for a manipulation check, and were not intended to tap into deep reading comprehension processes (e.g., inferential processes). Therefore, children's performance on these comprehension questions were not used in the analysis. However, to ensure that children included in the analysis are "readers"—that is, can read at least one passage and answer a simple literal comprehension question correctly—those who were not able to correctly answer a single comprehension question were excluded from the analysis. The percentages of children who answered 1, 2, or 3 comprehension questions, respectively, were as follows in each time point: 47%, 40%, and 12% in oral reading in the fall; 53%, 36%, and 11% in silent reading in the fall; 9%, 45%, and 46% in oral reading in the spring; and 12%, 45%, and 43% in silent reading in the spring. Note that the goal of the present study was to examine similarities and differences in online processing during oral and silent reading for *developing* readers. Therefore, it was not our intent that those included in the analysis should have *fully* developed reading skills.

An oral or silent reading session was discontinued if the child could not read a single word at all or exceeded five minutes on a passage. In addition, a silent reading session was discontinued if it was apparent to the experimenter that the child was not reading, based on erratic fixation patterns. These criteria resulted in the exclusion of 88 participants in silent reading and 68 participants in oral reading during the fall assessment and the exclusion of 12 and 5 participants in silent and oral reading, respectively, during the spring assessment. The higher number of exclusions in silent versus oral reading at both assessment points was due to children's randomly looking around the screen to a greater extent in the silent versus oral reading session.

Children's eye movements were captured by an unobtrusive desktop camera in front of the monitor using the EyeLink1000 system in combination with a forehead and chin rest. Texts were presented on a 21-inch monitor with a screen resolution of 1024 * 768 pixels. Courier New typeface in 15-point font size was used, and viewing distance was adjusted so that one letter corresponded to 0.33 degree of visual angle. Texts were presented in black color on a grey background with double line spacing. Passages were broken up into two to three paragraphs, each paragraph consisting of five to seven lines and presented on a separate screen. Children were encouraged to move as little as possible during the measurement but could move around between passages. Between passages, the camera was calibrated to ensure measurement accuracy using a 9-point calibration and validation. Then, right before the child read a passage, an additional drift correction check was performed. If deviations larger than 0.5 degree of visual angle were detected, the camera system was recalibrated. Eye movements were tracked at 500 Hz, and viewing and recording were binocular, though only data from the right eye were used for analyses.

Eye-movement data were processed and analyzed using EyeMap (Tang, Reilly, & Vorstius, 2012) and SPSS (see Appendix A for a detailed description of the eye-movement measures). In addition to excluding

participants who were not able to read based on the experimenters' judgment during data collection, data points with less than 100 fixations per paragraph were excluded from further analyses (< 2%, or 7 participants). The final data set included 560,969 fixations for the fall and 746,675 fixations for the spring assessment, with each participant contributing data from at least one passage.

### 4.3. Data analytic strategies

To answer research question 1 about eye-movement behaviors in oral and silent reading and their changes over time in Grade 1, repeated measures ANOVAs were conducted, with wave (fall vs. spring) and reading mode (oral vs. silent) as factors.[2] Type 1 family-wise error correction was applied where indicated (Bonferroni). The order of oral and silent reading sessions was counterbalanced within each wave, and analyses showed no effects of session order (see Appendix B). For research question 2 about the relations of eye-movement behaviors to reading proficiency, factor analysis was first conducted to examine the factor structure of the eye-movement parameters. Several alternative models were systematically examined, accounting for shared variance due to passages (see Fig. 1). In an initial model (Model 1), the following three factors were fitted based on adult proficient readers outlined in the literature review (see above): early orthographic processing factor, lexical semantic processing factor, and higher order integration factor. Measures reflecting early orthographic/visual and early lexical processing included first fixation duration and landing position. Lexical semantic processing was hypothesized to be captured in refixation duration, fixation count on the word, and the probability of making a refixation on the word. Finally, rereading time, the number of gazes per word, and the probability of making an interword regression were taken as indicators of higher order processing such as syntactical integration (Brysbaert et al., 2005; Clifton et al., 2007; Frazier & Rayner, 1982; Inhoff, 1984; Inhoff & Radach, 1998; Inhoff & Rayner, 1986; McConkie et al., 1988, 1989; O'Regan, 1981; Radach et al., 2008; Radach & Kempe, 1993; Radach & Kennedy, 2004; Rayner, 1998; Rayner & Duffy, 1986; Rayner & Pollatsek, 1987; Rayner et al., 1998, 2006; Reichle et al., 2003; White, 2007).

In addition, two alternative models were tested. First, a single-factor model (Model 2) was tested to examine whether all of the eye-tracking indexes are broadly tapping a single construct. Our expectation was not that this model would provide the best fit to the data, nor that it would conform to an explanatory model for individual differences; instead, this model would serve as a base-counterfactual to both correlated-trait factor models and more complex specifications. Second, we specified a second-order factor model (Model 3; see Appendix C for more details) that created sets of first-order latent constructs that were reflective of index-specific effects as well as the second-order constructs of early orthographic processing, lexical semantic processing, and higher order integration. We hypothesized that individual latent constructs might be formed for each index (e.g., a latent construct for first fixation duration indicated by first fixation duration on each of the passages 1–3). These first-order index-level factors were created for first fixation duration, initial landing position, refixation duration, number of fixations in first gaze, proportion of refixations, re-reading duration, number of gazes, and proportion of regressive saccades. The creation of the index-level factors alone was not expected to shed light on a theoretically meaningful structure of the eye-tracking data; instead, it served as a first step to unpack potential construct-relevant variance. Once the index-level factors were specified, second-order factors were then created to represent theoretical groupings of the first-order factors as follows: (a) First fixation duration and initial landing position were defined as part of a latent "initial orthographic" processing factor; (b) refixation duration, number of fixations in first gaze, and proportion of refixations were defined as part of a "lexical semantic" processing factor; and (c) re-reading duration, number of gazes, and proportion of regressions were defined as part of an "integration" factor. Models 1 and 3 are quite similar to each other in that they attempt to cluster indexes together to form three theoretically motivated factors; yet they are different in that Model 3 specifically accounts for shared variance at the index level due to multiple occurrences across passages (e.g., first fixation duration on paragraphs 1, 2, and 3). Model 2 then serves as a baseline model for examining whether all the indexes converge on a single construct.

Comparisons across these models were made using the following model fit indices: comparative fit index (CFI; Bentler, 1990), Tucker-Lewis index (TLI; Bentler & Bonnett, 1980), and root mean square error of approximation (RMSEA; Browne & Cudeck, 1992). CFI and TLI values greater than or equal to 0.95 are considered to be minimally sufficient criteria for acceptable model fit, and RMSEA estimates < 0.05 are desirable (Browne & Cudeck, 1992).

Based on the results from the factor analyses of eye-tracking data, the estimated factor scores were used to study the extent to which, on average, the eye-movement factor(s) predicted off-line latent reading proficiency scores (both word reading and reading comprehension; research question 2).[3] Then, we evaluated the extent to which the relation between eye movements in oral and silent reading and word reading and reading comprehension scores varied as a function of children's latent word reading proficiency and reading comprehension proficiency, respectively, using quantile regression (Koenker & Bassett, 1978; Petscher & Logan, 2014; Petscher, Logan, & Zhou, 2013). Quantile regression is a form of conditional median regression that estimates conditional relations between variables at other points of the distribution instead of the mean. As such, although ordinary least squares regression asks the question, "What is the relation between *x* and *y*, on average?" quantile regression is useful for understanding, "Does the relation between *x* and *y* vary conditional on *y*?" In the present study, the relations between the eye-movement general factor and latent word reading and reading comprehension were evaluated conditional on the distribution of latent word reading and reading comprehension, respectively. Both ordinary least squares and quantile regression analyses were conducted for comparative purposes. Prior to running the regression analyses, it was important to evaluate the factor score determinacy of the eye-tracking factor scores, as well as the word reading and reading comprehension outcomes. Because the regressions were run outside of a latent variable framework, factors and factor scores are typically not perfectly correlated. Factor score determinacy is a value ranging from 0 to 1 and may be interpreted as the correlation between a factor in a latent variable model and the factor score. Values greater than 0.80 are deemed sufficient for use in secondary analysis as there would be a very strong association between the factor and the factor score (Gorsuch, 1983). Mplus software was used for all factor analyses, and SAS software was used for ordinary least squares and quantile regression analyses.

## 5. Results

### 5.1. Descriptive statistics and preliminary analysis

Descriptive statistics for the reading measures and eye-movement measures are reported in Tables 1 and 2, respectively. Appendix A

[2] Note that we also ran between-subject analyses using each participant's first reading session (oral or silent) at each time point only. These analyses yielded similar results to the repeated measures within-subject analyses reported in this paper.

[3] In order to leverage the commonality between the two word reading measures, a confirmatory factor analysis was used to estimate latent word reading ability scores for both the fall and spring. The word reading factor model demonstrated excellent fit, $\chi^2(1) = 0.61$, CFI = 1.00, TLI = 1.00, RMSEA = 0.000 (0.000, 0.126). The reading comprehension factor model also demonstrated excellent model fit, $\chi^2(1) = 1.05$, CFI = 1.00, TLI = 1.00, RMSEA = 0.012 (0.000, 0.139).

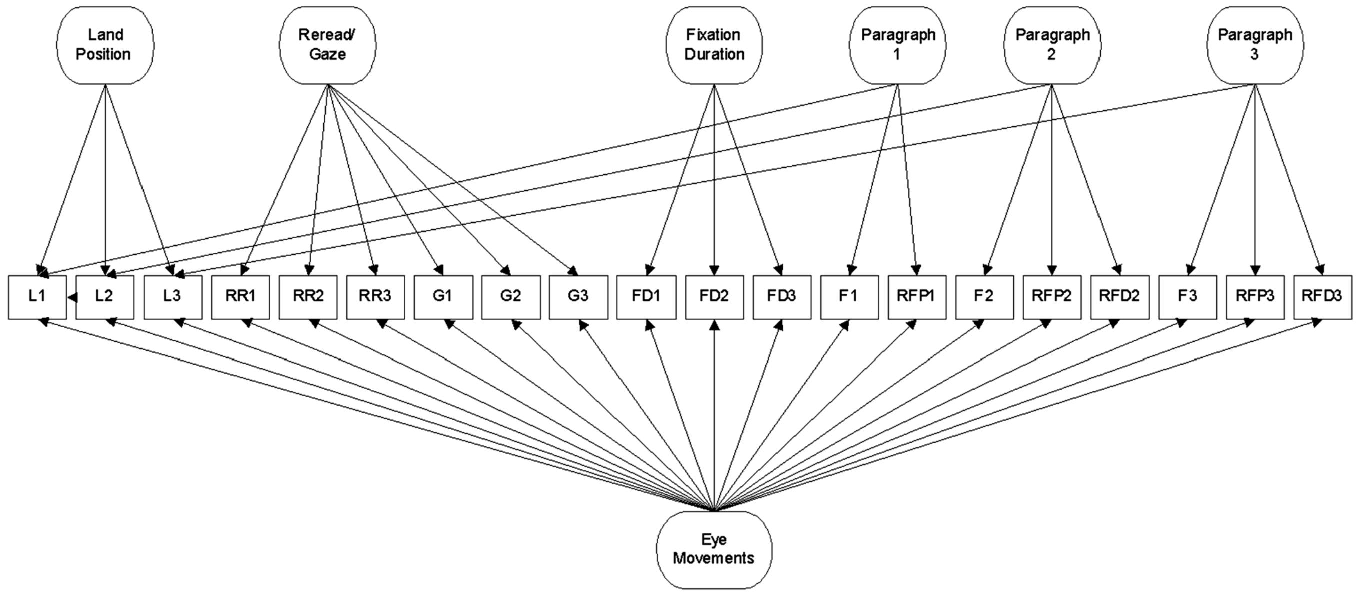


**Fig. 1.** Bi-factor model of eye movements. Note that all the eye movement indicators in Table 2 as well as passages were accounted for, but for illustrative purposes, only a few eye movement indicators are shown in the diagram. Numbers represents passage numbers. L = Landing position; RR = Rereading duration; FD = Fixation duration; G = Number of Gazes; F = Number of fixations per gaze; RFP = Proportion of Refixations; RFD = Refixation Duration (gaze 2–6).

presents descriptive statistics for eye-movement measures by passage. Standard scores for the reading proficiency measures (Table 1) indicate that, compared to a norm sample, mean performances on the word reading tasks were in the average or high average range in the fall and spring, and mean performances on the reading comprehension tasks were in the average range in the fall and spring. These scores indicate that children in the present study, on average, were developing at an expected rate in reading compared to a norm sample.

Correlations among the eye-movement behaviors in oral and silent reading and reading proficiency measures in the fall and spring of Grade 1 are presented in Tables 3 and 4, respectively. Correlations between eye-movement behaviors ranged from minimal (e.g., −0.03 between first fixation duration and proportion of regressions in the oral reading mode in the fall) to extremely strong (0.95 between number of fixations in gaze and proportion of refixations in the silent reading mode in the fall). Consistent with previous studies, off-line reading proficiency measures were highly correlated with each other. Correlations between online eye movements and off-line reading proficiency measures varied, but overall tended to range from relatively weak to moderate in the fall and spring and tended to be larger for the oral compared to the silent reading mode. This difference based on reading mode is best illustrated in the relations between initial landing position and reading proficiency in the fall: In the oral reading mode, initial landing position was moderately related to word reading and reading comprehension ($0.27 \le rs \le 0.40$); in the silent reading mode, initial landing position was minimally or not at all related to the reading proficiency measures ($-0.07 \le rs \le 0.01$).

### *5.2. Research question 1: Characteristics of eye-movement behaviors in oral and silent reading in the beginning and end of the school year for beginning readers*

Overall, we found a pattern of reductions in reading times, refixations, and gazes per word from fall to spring. In addition, clear differences were found for reading mode (oral vs. silent). Descriptive statistics and effect sizes between oral and silent reading (i.e., standardized mean differences, Cohen's *ds*) in the fall and spring for all eye-movement measures are presented in Table 2 as well as differences between fall and spring in oral reading mode and silent reading mode, respectively. ANOVA results are presented in Table 5.

For first fixation duration, we found significant main effects for wave and reading mode with shorter durations in spring and in silent reading, but no significant interaction. However, looking at the descriptive data, it is apparent that although statistically significant, changes in first fixation durations were rather small (4% overall reduction from fall to spring). Far greater changes were found for refixation duration and rereading time. For refixation duration, both the main effects and the interaction were significant. Refixation durations were longer in fall compared to spring and longer in oral compared to silent reading, but the difference between reading modes was significantly more pronounced in fall than in spring. Results indicated significant reductions in refixation duration from fall to spring for both oral (93 ms) and silent (41 ms) reading as well as significant differences between reading modes in fall (98 ms) and spring (45 ms) waves.

**Table 1**
Descriptive statistics for reading measures.

| Measures | Fall | | | | Spring | | | |
|---|---|---|---|---|---|---|---|---|
| | Raw score | | Standard score | | Raw score | | Standard score | |
| | Mean | SD | Mean | SD | Mean | SD | Mean | SD |
| WJIII – LWID | 33.73 | 6.54 | 112.91 | 12.93 | 39.03 | 6.28 | 114.87 | 12.21 |
| WIAT-Word Reading | 15.70 | 9.71 | 102.31 | 16.21 | 23.89 | 9.59 | 107.76 | 15.21 |
| WIAT-Reading Comp | 15.30 | 8.48 | 101.67 | 14.01 | 23.35 | 7.43 | 107.08 | 14.10 |
| WJIII – Passage Comp | 16.83 | 4.43 | 104.37 | 13.65 | 21.96 | 3.56 | 108.67 | 11.68 |

WJ-III = Woodcock Johnson-III; WIAT = Wechsler Individual Achievement Test; Comp = Comprehension; LWID = Letter Word Identification; Comp = Comprehension.

**Table 2**
Means, standard deviations, and mean standardized difference (Cohen's d) between oral and silent reading for key eye movement parameters by assessment time (fall & spring) and oral and silent reading conditions.

| | Fall | | | | | Spring | | | | | Fall-spring difference | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Silent | | Oral | | ES* | Silent | | Oral | | ES* | Silent | Oral |
| Measures | Mean | SD | Mean | SD | | Mean | SD | Mean | SD | | ES | ES |
| First fixation duration | 334.82 | 69.12 | 354.33 | 71.78 | 0.28 | 317.74 | 61.21 | 341.85 | 69.85 | 0.37 | 0.26 | 0.18 |
| Refixation duration | 218.83 | 130.81 | 316.56 | 192.67 | 0.60 | 178.22 | 99.91 | 223.24 | 119.59 | 0.41 | 0.35 | 0.60 |
| Rereading time | 374.80 | 337.79 | 718.02 | 704.66 | 0.66 | 266.84 | 198.53 | 401.16 | 288.62 | 0.55 | 0.40 | 0.64 |
| Number of fixations in gaze | 1.59 | 0.26 | 1.78 | 0.33 | 0.64 | 1.53 | 0.22 | 1.62 | 0.25 | 0.38 | 0.25 | 0.55 |
| Number of gazes on word | 1.63 | 0.36 | 1.98 | 0.76 | 0.63 | 1.53 | 0.27 | 1.71 | 0.36 | 0.57 | 0.32 | 0.48 |
| Proportion of refixations | 0.35 | 0.09 | 0.41 | 0.10 | 0.63 | 0.32 | 0.08 | 0.36 | 0.09 | 0.47 | 0.35 | 0.53 |
| Proportion of regressions | 0.31 | 0.06 | 0.31 | 0.06 | 0.00 | 0.29 | 0.06 | 0.29 | 0.05 | 0.00 | 0.33 | 0.36 |
| Initial landing position | 2.07 | 0.25 | 1.91 | 0.23 | −0.67 | 2.00 | 0.22 | 1.92 | 0.18 | −0.40 | 0.30 | −0.05 |
| Rereading time (gaze 2–6) | 258.27 | 334.98 | 465.31 | 629.97 | 0.43 | 173.83 | 164.25 | 260.90 | 255.06 | 0.42 | 0.34 | 0.46 |
| Refixation duration (gaze 2–6) | 203.49 | 148.22 | 292.38 | 205.46 | 0.50 | 155.12 | 110.75 | 188.16 | 121.33 | 0.28 | 0.37 | 0.64 |

Note. ES = Effect Size in Cohen's d; ES* = difference between silent and oral model in the fall and spring, respectively; First fixation duration = duration of the initial fixation on a word; Refixation duration = time spent on the word in the first gaze after the initial fixation and before moving to the next word; Rereading time = time spent on the word after the first gaze; Number of gazes on word = instances in which the word received one or more fixations before another word was fixated; Number of fixations in gaze = number of fixations during a single gaze; Proportion of refixations = proportion of refixations, based on all fixations; Initial landing position = location of the first fixation in the word (letter position); In addition to the first pass parameters, we included information from gazes 2–6 (together with gaze 1 representing ~99% of all fixations) for the factor analyses (see Appendix B for details) to capture as much eye movement behavior as possible. Refixation duration (gaze 2–6) = mean time spent on a word after the initial fixation in gazes 2–6; Rereading time (gaze 2–6) = mean time spent rereading a word in gaze 2–6.

Refixation durations were 44% longer for oral reading than for silent reading in fall ($d$ = 0.60), but only 25% longer in spring ($d$ = 0.41).

Prominent differences were found for rereading times, including significant main effects for wave and reading mode and a significant interaction. Results indicated significant reductions in rereading times from fall to spring for both oral (317 ms) and silent (108 ms) reading as well as significant differences between reading modes in fall (334 ms) and spring (134 ms) waves. The difference in rereading times for oral versus silent reading was large in the fall ($d$ = 0.66), and smaller, but still substantial in the spring ($d$ = 0.55). Across reading modes, rereading times decreased by 36% from fall to spring. However, the decrease from fall to spring for oral reading (44%) was much more pronounced than that for silent reading (29%).

Not only reading times, but also fixation patterns showed development across time points and differences between reading modes. We found fewer fixations per gaze in spring than in fall and in silent reading than in oral reading. Results showed a significant reduction in the number of fixations from fall to spring for both oral (0.16 fixations per gaze) and silent (0.06 fixations per gaze) reading, as well as significant differences between reading modes in fall (0.19 fixations per gaze) and spring (0.09 fixations per gaze) waves. The significant interaction indicated again that the difference between reading modes was less pronounced in spring than in fall. The same pattern was found for the number of gazes per word, with significant main effects for wave and reading mode, as well as a significant interaction. Again, main effects showed a significantly lower number of gazes per word in the spring than in the fall and in silent reading than in oral reading. There was a reduction in the number of gazes per word from fall to spring for both oral reading (0.27 gazes per word) and silent reading (0.10 gazes per word), as well as significant differences between reading modes in fall (0.35 gazes per word) and spring (0.18 gazes per word) waves. The proportion of refixations also shows a pattern in line with the findings reported above. Refixations decreased significantly from fall to spring and occurred more often in oral reading. Results indicated a significant reduction in the proportion of fixations from fall to spring for both oral (0.03) and silent (0.05) reading, as well as significant differences between reading modes in fall (0.06) and spring (0.04) waves.

The overall proportion of interword regressions showed a significant main effect for wave with a reduction from fall to spring, but no effect for reading mode ($d$ = 0) and no interaction. Finally, for initial landing position within words, the main effect for wave was not significant. However, there was a significant main effect of reading mode as well as a significant interaction. Initial fixations in words were more towards the beginning of the word in oral reading. Initial landing positions from

**Table 3**
Fall correlations among eye-movement indices and reading achievement measures based on oral (upper diagonal) and silent (lower diagonal) reading.

| Measures | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1. First fixation duration | – | −0.48 | 0.59 | 0.39 | 0.39 | 0.24 | 0.16 | 0.10* | −0.03* | 0.42 | −0.39 | −0.44 | −0.36 | −0.42 |
| 2. Initial landing position | −0.36 | – | −0.62 | −0.65 | −0.63 | −0.33 | −0.23 | −0.24 | 0.10* | −0.37 | 0.36 | 0.40 | 0.27 | 0.29 |
| 3. Refixation duration | 0.62 | −0.58 | – | 0.93 | 0.85 | 0.44 | 0.29 | 0.24 | 0.17 | 0.73 | −0.47 | −0.53 | −0.43 | −0.47 |
| 4. Number of fixations in gaze | 0.37 | −0.66 | 0.89 | – | 0.92 | 0.37 | 0.24 | 0.21 | 0.10* | 0.62 | −0.42 | −0.48 | −0.37 | −0.41 |
| 5. Proportion of refixations | 0.38 | −0.64 | 0.86 | 0.95 | – | 0.47 | 0.33 | 0.31 | 0.24 | 0.73 | −0.54 | −0.59 | −0.46 | −0.53 |
| 6. Rereading time | 0.37 | −0.34 | 0.65 | 0.52 | 0.59 | – | 0.90 | 0.95 | 0.62 | 0.53 | −0.51 | −0.54 | −0.50 | −0.53 |
| 7. Rereading time (2–6) | 0.26 | −0.18 | 0.42 | 0.32 | 0.39 | 0.68 | – | 0.88 | 0.51 | 0.44 | −0.38 | −0.41 | −0.40 | −0.42 |
| 8. Number of gazes in word | 0.15 | −0.31 | 0.43 | 0.40 | 0.45 | 0.90 | 0.59 | – | 0.61 | 0.31 | −0.46 | −0.47 | −0.43 | −0.47 |
| 9. Proportion of regressions | −0.12* | 0.36 | −0.03* | −0.12* | −0.08* | 0.36 | 0.25 | 0.46 | – | 0.42 | −0.48 | −0.49 | −0.46 | −0.51 |
| 10. Refixation duration (2–6) | 0.50 | −0.33 | 0.76 | 0.62 | 0.70 | 0.63 | 0.52 | 0.40 | 0.12* | – | −0.49 | −0.53 | −0.45 | −0.51 |
| 11. WJ-III Letter Word ID | −0.34 | 0.03* | −0.36 | −0.26 | −0.35 | −0.33 | −0.27 | −0.21 | −0.39 | −0.43 | – | 0.90 | 0.76 | 0.84 |
| 12. WIAT-III Word reading | −0.35 | 0.04* | −0.39 | −0.29 | −0.37 | −0.36 | −0.28 | −0.25 | −0.39 | −0.45 | 0.90 | – | 0.78 | 0.85 |
| 13. WIAT-III Reading Comp | −0.27 | −0.07* | −0.31 | −0.22 | −0.29 | −0.28 | −0.24 | −0.17 | −0.36 | −0.36 | 0.74 | 0.76 | – | 0.80 |
| 14. WJ-III Passage Comp | −0.35 | 0.01* | −0.36 | −0.23 | −0.30 | −0.35 | −0.31 | −0.24 | −0.42 | −0.41 | 0.83 | 0.85 | 0.78 | – |

WJ = Woodcock Johnson-III; WIAT = Wechsler Individual Achievement Test; Comp = Comprehension; Rereading time (2–6) = Rereading time (gaze 2–6); Refixation duration = Refixation duration (gaze 2–6). *$p$ > .05.

**Table 4**
Spring correlations among eye-movement indices and reading achievement measures based on oral (upper diagonal) and silent (lower diagonal) reading.

| Measures | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 14 | 14 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1. First fixation duration | – | −0.42 | 0.67 | 0.33 | 0.39 | 0.42 | 0.31 | 0.16 | −0.06* | 0.57 | −0.52 | −0.51 | −0.40 | −0.44 |
| 2. Initial landing position | −0.44 | – | −0.62 | −0.59 | −0.60 | −0.36 | −0.26 | −0.23 | 0.12* | −0.41 | 0.40 | 0.41 | 0.31 | 0.35 |
| 3. Refixation duration | 0.64 | −0.64 | – | 0.85 | 0.85 | 0.61 | 0.44 | 0.37 | 0.12* | 0.73 | −0.57 | −0.60 | −0.46 | −0.52 |
| 4. Number of fixations in gaze | 0.44 | −0.66 | 0.93 | – | 0.96 | 0.49 | 0.35 | 0.34 | 0.09* | 0.59 | −0.52 | −0.55 | −0.40 | −0.47 |
| 5. Proportion of refixations | 0.47 | −0.64 | 0.90 | 0.97 | – | 0.58 | 0.44 | 0.43 | 0.13* | 0.67 | −0.62 | −0.64 | −0.48 | −0.55 |
| 6. Rereading time | 0.44 | −0.41 | 0.67 | 0.59 | 0.61 | – | 0.79 | 0.92 | 0.62 | 0.61 | −0.63 | −0.64 | −0.51 | −0.57 |
| 7. Rereading time (2–6) | 0.36 | −0.27 | 0.50 | 0.44 | 0.47 | 0.84 | – | 0.74 | 0.46 | 0.58 | −0.44 | −0.44 | −0.30 | −0.37 |
| 8. Number of gazes in word | 0.21 | −0.34 | 0.46 | 0.46 | 0.47 | 0.92 | 0.78 | – | 0.74 | 0.42 | −0.53 | −0.55 | −0.44 | −0.50 |
| 9. Proportion of regressions | −0.10* | 0.34 | −0.05* | −0.06* | −0.03* | 0.34 | 0.33 | 0.43 | – | 0.16 | −0.26 | −0.29 | −0.25 | −0.31 |
| 10. Refixation Duration (2–6) | 0.45 | −0.30 | 0.59 | 0.53 | 0.60 | 0.56 | 0.60 | 0.37 | 0.16 | – | −0.60 | −0.60 | −0.46 | −0.50 |
| 11. WJ-III Letter Word ID | −0.49 | 0.20 | −0.45 | −0.39 | −0.46 | −0.35 | −0.28 | −0.16 | −0.13* | −0.44 | – | 0.89 | 0.68 | 0.75 |
| 12. WIAT-III Word reading | −0.47 | 0.23 | −0.46 | −0.41 | −0.48 | −0.37 | −0.29 | −0.18 | −0.12* | −0.46 | 0.88 | – | 0.70 | 0.78 |
| 13. WIAT-III Reading Comp | −0.32 | 0.15 | −0.29 | −0.25 | −0.30 | −0.20 | −0.16 | −0.05* | −0.14 | −0.35 | 0.64 | 0.67 | – | 0.75 |
| 14. WJ-III Passage Comp | −0.44 | 0.21 | −0.40 | −0.33 | −0.40 | −0.30 | −0.23 | −0.12* | −0.14 | −0.41 | 0.75 | 0.77 | 0.72 | – |

WJ = Woodcock Johnson-III; WIAT = Wechsler Individual Achievement Test; Comp = Comprehension; Rereading time (2–6) = Rereading time (gaze 2–6); Refixation duration = Refixation duration (gaze 2–6). *$p > .05$.

fall to spring shifted slightly to the left for oral (−0.01 letters) and to the right for silent (0.07 letters) reading. In addition, in fall the difference between reading modes for initial landing positions was more pronounced (−0.16 letters) compared to in spring (−0.08 letters).

Taken together, these changes in eye-movement measures reflect that children made large gains in reading skills in first grade and are in line with results reported in previous studies with children (e.g., Blythe & Joseph, 2011; Tiffin-Richards & Schroeder, 2015; Vorstius et al., 2014). Despite the gains in reading development, however, eye-movement measures in the spring of first grade are still distinct from proficient adult readers, mostly due to prolonged viewing times (e.g., first fixation duration was 335 ms for this sample compared to ~225 ms for adults in silent reading; Rayner, 1998).

### *5.3. Research question 2: The relation of eye movements to reading proficiency*

As noted above, prior to examining the relation of eye movements to reading proficiency, several alternative factor models were systematically compared. As detailed in Appendix C, the three models planned a priori did not fit the data well. The lack of acceptable model fit for any of the hypothesized models led to the specification of exploratory factor analyses (EFAs) using the same indexes to identify the extent to which a simple solution with acceptable fit and theoretically meaningful relations could be established. The patterns found in the EFAs (see Appendix C for details) led to the specification of a bi-factor model in order to test for the presence of index-specific factors, paragraph-specific factors, and then a general factor of eye movements. Bi-factors have been found to be useful in understanding data structures where there are either theoretical or observed strong relations among what is being measured (Connor et al., 2015; Kieffer, Petscher, Proctor, & Silverman, 2016; Reise, 2012). Using the bi-factor model approach, we hypothesized that a general factor of eye movements might exist along with one or more specific, residual factors. Specifically, we tested for a general factor of eye movements along with specific factors related to initial landing position, rereading duration/number of gazes, fixation duration, and three factors related to passage-specific effects (i.e., passages 1, 2, and 3).

Results revealed that a bi-factor model (Fig. 1) fitted the data best at the fall and spring for both silent and oral reading [e.g., Fall Silent: $\chi^2(138) = 339.09$, CFI = 0.96, TLI = 0.95, RMSEA = 0.08; Fall Oral: $\chi^2(138) = 464.99$, CFI = 0.95, TLI = 0.93, RMSEA = 0.09; Spring Silent: $\chi^2(138) = 441.53$, CFI = 0.96, TLI = 0.94, RMSEA = 0.08; Spring Oral: $\chi^2(139) = 568.65$, CFI = 0.95, TLI = 0.93, RMSEA = 0.09]. Standardized loadings for each measurement occasion by reading mode are reported in Appendix D. The resulting structure included one general factor of eye movements (which captured common variance among all the eye-movement variables) along with six residual factors corresponding to either an eye-movement index-specific construct (i.e., fixation duration, rereading duration/number of gazes, initial landing position) or a passage-specific construct (i.e., passages 1, 2, and 3). The general factor captured all the eye-movement indicators shown in Table 2 and therefore indicates the child's overall eye-movement control. We, then, evaluated the general factor score determinacy values for all outcomes by wave and reading mode: 0.93 (fall eye movements, oral reading), 0.92 (fall eye movements, silent reading), 0.92 (spring eye movements, oral reading), 0.92 (spring eye movements, silent reading), 0.98 (fall word reading), 0.95 (spring word reading), 0.96 (fall reading comprehension), and 0.95 (spring reading

**Table 5**
F- and p values for repeated measures ANOVA and simple effects follow-ups for significant interaction terms.

| | ANOVA | | | | | | Simple effects | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Main effects | | | | Interaction | | Wave | | | | Reading mode | | | |
| | Wave | | Reading mode | | Wave × reading mode | | Silent | | Oral | | Fall | | Spring | |
| Measure | $F_{(1,175)}$ | p | $F_{(1,175)}$ | p | $F_{(1,175)}$ | p | $F_{(1,175)}$ | p | $F_{(1,175)}$ | p | $F_{(1,175)}$ | p | $F_{(1,175)}$ | p |
| First fixation duration | 59.00 | < 0.001 | 35.37 | < 0.001 | 2.66 | 0.11 | | | | | | | | |
| Refixation duration | 94.05 | < 0.001 | 84.00 | < 0.001 | 29.89 | < 0.001 | 37.83 | < 0.001 | 96.70 | < 0.001 | 70.81 | < 0.001 | 41.35 | < 0.001 |
| Rereading time | 76.04 | < 0.001 | 82.31 | < 0.001 | 31.47 | < 0.001 | 25.54 | < 0.001 | 72.27 | < 0.001 | 62.24 | < 0.001 | 36.44 | < 0.001 |
| Number of fixations in gaze | 78.82 | < 0.001 | 88.29 | < 0.001 | 29.63 | < 0.001 | 18.29 | < 0.001 | 91.82 | < 0.001 | 81.54 | < 0.001 | 26.33 | < 0.001 |
| Number of gazes on word | 46.61 | < 0.001 | 75.35 | < 0.001 | 20.97 | < 0.001 | 9.66 | 0.002 | 46.61 | < 0.001 | 54.28 | < 0.001 | 28.59 | < 0.001 |
| Proportion of refixations | 130.58 | < 0.001 | 108.5 | < 0.001 | 37.92 | < 0.001 | 32.07 | < 0.001 | 183.13 | < 0.001 | 105.22 | < 0.001 | 30.57 | < 0.001 |
| Proportion of regressions | 39.00 | < 0.001 | 0.13 | 0.72 | 1.40 | 0.24 | | | | | | | | |
| Initial landing position | 1.01 | 0.32 | 59.46 | < 0.001 | 13.45 | < 0.001 | 9.14 | 0.003 | 3.96 | 0.048 | 52.18 | < 0.001 | 18.85 | < 0.001 |

comprehension). All values were deemed adequate according to Gorsuch (1983) for using estimated factor scores in subsequent regression models. The factor score determinacies for the specific, residual factors in the bi-factor model (i.e., passage and index factors) were also evaluated. However, these fell below acceptable guidelines (≤0.80) and, thus, were not used for further modeling. As noted above, for word reading and reading comprehension, latent variables were created using confirmatory factor analysis, respectively.

To address the question about the relation of eye movements to reading proficiency (both word reading and reading comprehension), correlations between the general eye-movement factor and word reading proficiency by wave and reading mode are illustrated in Fig. 2a–d (see the blue line labeled as OLS). The simple, concurrent bivariate associations via ordinary least squares (OLS) between the general eye-movement factor and the word reading factor were $r = -0.62$ (fall, oral reading), $r = -0.47$ (fall, silent reading), $r = -0.54$ (spring, oral reading), and $r = -0.39$ (spring, silent reading). In other words, children who had a high score on the general eye-movement factor (high values on the general eye movement factor represent low efficiency in processing in the included eye movement variables; e.g., the longer time the child spent on fixating words, the more frequently the child regressed back to words) had lower word reading skill, on average. Furthermore, eye movements during oral reading had stronger relations to word reading proficiency than eye movements during silent reading, on average, in the fall and spring. Correlations between eye movements and reading comprehension (Fig. 3a–d) were $r = -0.59$ (fall, oral reading), $r = 0.49$ (fall, silent reading), $r = -0.45$ (spring, oral reading), and $r = -0.30$ (spring, silent reading). Similar to the word reading outcomes, the general eye-movement factor was associated with lower reading comprehension.

An important point to note here is that these correlations represent the *average* across children with varying proficiency in word reading. However, Figs. 2 and 3 highlight that the average association estimated by traditional regression potentially obfuscates other meaningful *conditional* relations as a function of the child's word reading proficiency level. As an illustration, Fig. 2a shows the dependent-variable conditional relation between eye movements during oral reading and word reading in the fall. On the x-axis is children's conditional word reading proficiency at quantile intervals, and on the y-axis are the coefficients between eye movements (i.e., the general factor of eye movements) and word reading. Note that the process plot trend line in Fig. 2a demonstrates that coefficients ranged from $\sim -0.05$ for children with low word reading proficiency compared to $\sim -0.80$ for those with high word reading proficiency. Therefore, the OLS conditional mean coefficient (i.e., correlation) of $-0.62$ in the fall for oral reading skills is an overestimation of the relation for students with conditionally weak word reading skills and is simultaneously an underestimation of the relation for students with conditionally strong word reading skills. This type of trend was also observed in the fall for silent reading (Fig. 2b) whereby the OLS conditional mean coefficient was $-0.47$ but the relations along other conditional points of the word reading distribution ranged from $-0.11$ to $-0.62$.

An interesting trend is that at the spring assessment, the range of coefficients for both silent and oral reading tended to flatten out (Fig. 2c and Fig. 2d). This trend indicates that by the spring of first grade, the relations between eye movements and word reading are fairly stable for most students. It is worth pointing out that despite the more constant relation across the distribution of word reading skills, eye movements in the spring were less predictive of word reading performance for students with conditionally poor reading skills (i.e., $\sim < 0.30$ quantile) than for those with conditionally higher reading proficiency.

Quantile results for the reading comprehension outcome generally followed the same pattern as word reading. At low proficiency levels of reading comprehension, eye movements continued to be less predictive of the reading comprehension outcome than the OLS conditional mean coefficients (i.e., correlations) suggested. For example, for fall oral reading (Fig. 3a), the OLS estimate of $-0.59$ at the conditional mean overestimates the relation for students with conditionally poor reading comprehension as the relation consistently drops at lower quantiles of reading comprehension (i.e., $-0.18$ at the 0.10 quantile to $-0.58$ at the 0.40 quantile), yet it also underestimates the stronger relations observed at the conditionally higher quantiles of reading comprehension (i.e., $-0.65$ at the 0.60 quantile to $-0.75$ at the 0.90 quantile). Fall silent reading paralleled the pattern of fall oral reading (Fig. 3b). Note that in the spring, for oral reading the relation between eye movements and reading comprehension largely stabilized for students who were at or above the 0.40 quantile whereas for silent reading the relation stabilized at about the 0.60 quantile.

## 6. Discussion

The goals of the present study were (1) to compare online processes during reading as measured by eye movements in oral versus silent reading at the beginning and end of first grade and (2) to investigate the relations of eye-movement behaviors to reading proficiency (i.e., word reading and reading comprehension), including whether the relations varied as a function of children's reading proficiency. The target population in this study was beginning developing readers and by definition, these children have not fully developed reading skills. However, we made efforts to ensure that all the children in the analysis were readers based on our criterion of being able to answer at least one single simple comprehension question after reading a passage; and therefore, nonreaders were excluded from analyses. Results from this study should be interpreted with this in mind.

Overall, our longitudinal data revealed an emerging picture about online reading processes in oral and silent modes and the development of these processes for beginning readers over the first grade, a time period when reading development occurs at a rapid pace. Our data showed a developmental pattern in eye movements characterized by a significant decrease in all temporal measures, number of fixations per gaze, number of gazes per word, and proportions of refixations and regressions from the beginning to end of first grade. Changes in some measures from the beginning to end of the school year were drastic (e.g., rereading time and refixation duration). These changes indicate that rapid advances occur in first grade in children's ability to guide their eye movements for the purpose of efficient extraction of information from written text and are in line with results from smaller experimental studies (see Blythe & Joseph, 2011; Reichle et al., 2013, for reviews) as well as larger cross-sectional studies (Tiffin-Richards & Schroeder, 2015; Vorstius et al., 2014).

The present findings also highlight differences in oral and silent reading. Children looked at words with more fixations and gazes and for a longer time during oral reading than during silent reading at both the beginning and end of the year. Particularly pronounced differences were found between oral and silent reading in refixation duration (effect size $ds = 0.60$ in fall and 0.41 in spring) and rereading time ($ds = 0.66$ in fall and 0.55 in spring), compared to first fixation duration ($ds = 0.28$ in fall and 0.37 in spring). In other words, children spent a much longer time during oral reading looking at the word before leaving the word (i.e., refixation duration) and in the total time spent looking at the word (i.e., rereading time, which accounts for revisiting the word after leaving the word). This went hand in hand with more frequent fixations on a word ($ds = 0.64$ in fall and 0.38 in spring) and with more occasions of looking at a word ($ds = 0.63$ in fall and 0.57 in spring) during oral reading than silent reading, indicating that both processes—when and where to move the eyes—are influenced by reading mode in beginning readers. Previous studies have shown that it takes readers (children and adults) more time to read text orally than silently (Ashby et al., 2012; Vorstius et al., 2014). In addition, it has been speculated that when reading aloud, readers must devote cognitive resources to additional processes such as pronunciation, intonation, and monitoring (Jones & Lockhart, 1919), costing a greater processing

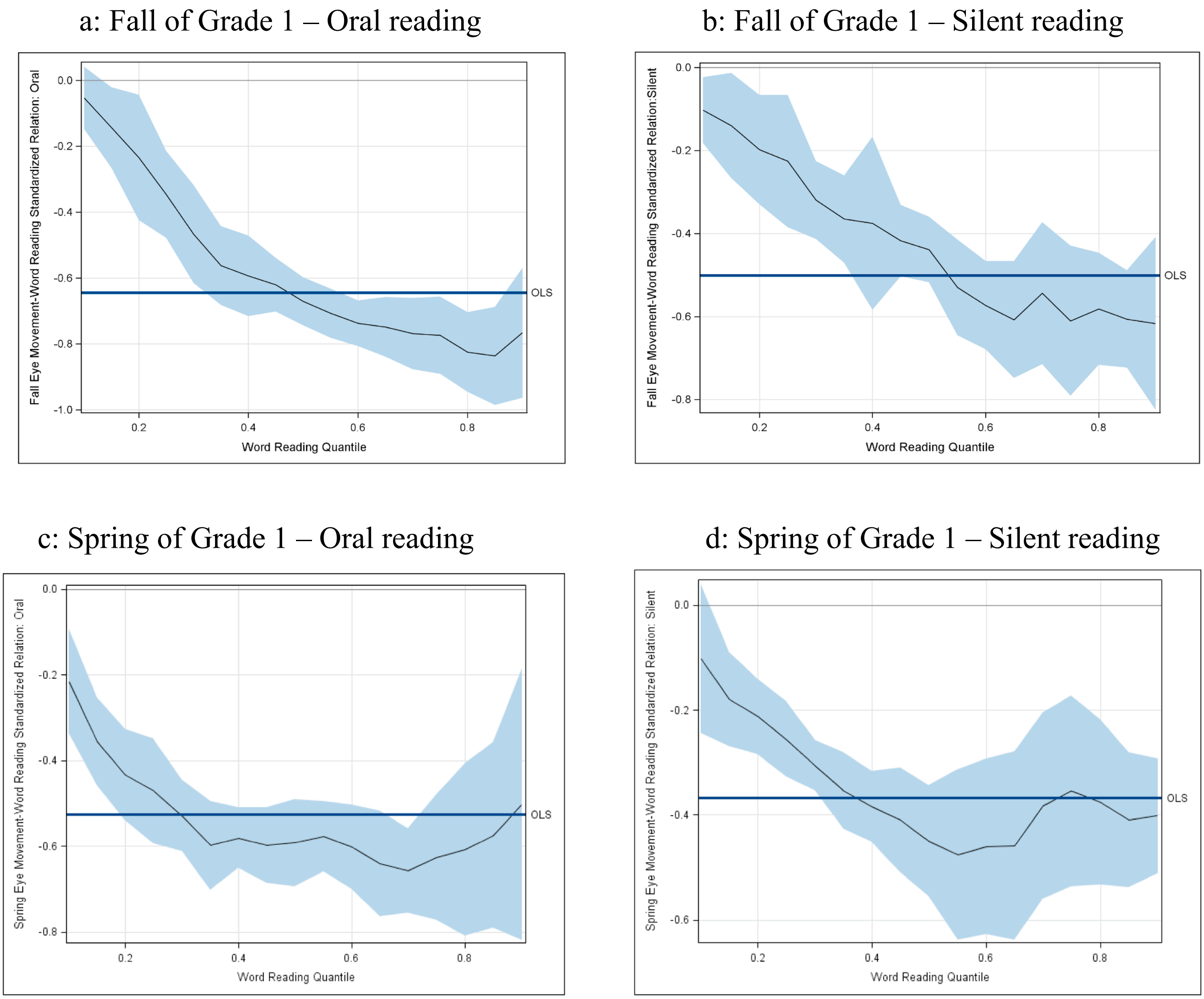


**Fig. 2.** Magnitudes of standardized relations between eye-movement and reading word proficiency (Y axis) as a function of children's level of word reading proficiency (X axis). Note that the scaling of values varies for the y-axis in each of the figures.

time. The present study adds to this growing literature about oral versus silent reading by revealing that large differences between oral and silent reading are due to much greater time spent on refixating and rereading the word as well as looking at the words more frequently during oral reading. The fact that differences between oral and silent reading are more pronounced in the fall suggests that the additional processes during reading aloud are more difficult to coordinate particularly during the very beginning phase of reading development. However, changes in eye movement behaviors from fall to spring tended to be larger in oral reading mode, indicating greater development in eye movement behaviors in oral reading during Grade 1, which explains the smaller differences between silent and oral reading in eye movement behaviors in spring.

Interestingly, we also found an effect of reading mode on the location where the initial fixation within a word lands (initial landing position). When reading aloud, children's eyes landed more to the left within a word than during silent reading. Taken together with the increased number of fixations on a word during oral reading, this pattern makes sense and indicates a reading-mode dependent strategic adjustment of the oculomotor system. Apparently, acquiring visual information is more difficult when reading aloud. As more visual samples (i.e., fixations) of the word are taken to accomplish decoding, the first landing position is shifted towards the word beginning, allowing for further informative visual samples of the word Blythe, 2015; Vorstius et al., 2014). Alternative explanations could be restrictions imposed by the articulatory system when reading aloud. In any case, the fact that such a strategic adjustment is already found in young beginning readers is quite impressive and suggests that automatic processes (see above) are influencing information acquisition from the beginning stage of reading development. These findings are also in line with the idea that at this stage, children cannot benefit from parafoveal preview to the same extent that adult readers can (Sperlich et al., 2015, 2016). One might note that the present data set would allow for more fine-grained analyses of the eye-movement data (e.g., regarding the origin and targets of regressive/rereading saccades). While this is certainly true, and results from such analyses will help to explore and gain a further understanding of ongoing processes, this is beyond the scope of the present study, and a more in-depth analysis of the eye-tracking data will be presented in future work.

Turning to the relation of eye movements and reading skills (both [oral] word reading and [silent] reading comprehension), we found that the average correlation was stronger in oral reading than in silent reading, both in the fall and spring. This was the case in bivariate correlations between each eye-movement indicator and reading proficiency

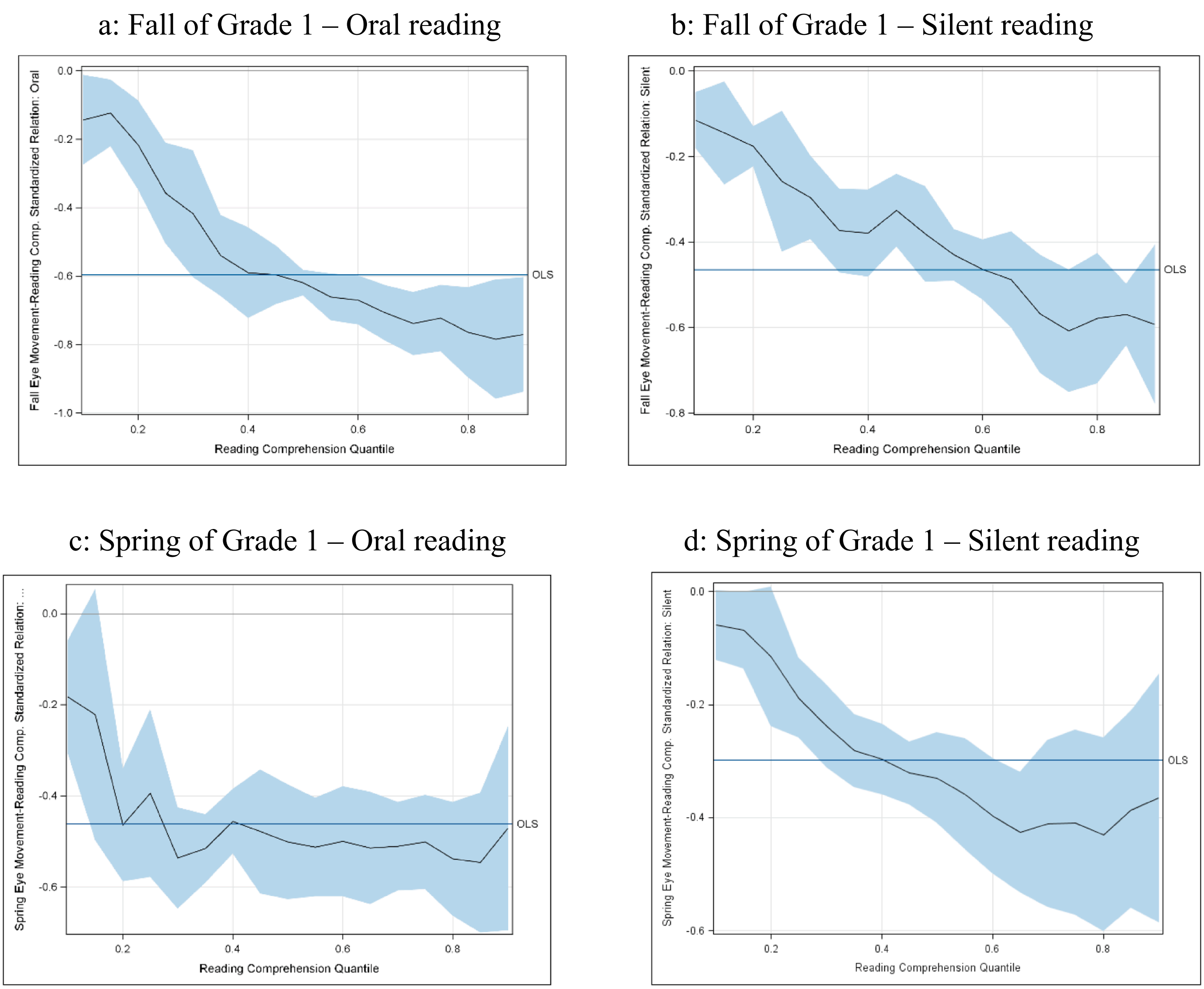


**Fig. 3.** Magnitudes of standardized relations between eye-movement and reading comprehension proficiency (Y axis) as a function of children's level of reading comprehension proficiency (X axis). Note that the scaling of values varies for the y-axis in each of the figures.

(see Tables 3 and 4), which showed that eye movements during silent reading tended to be weakly to moderately related with reading proficiency whereas eye movements during oral reading had more stable and robust moderate associations with reading proficiency. Interestingly, where children landed (initial landing position) in the beginning of the year during silent reading was not related to reading proficiency whereas it was for oral reading. Stronger magnitudes of relations between eye movements and reading proficiency were also observed at the construct level (i.e., latent variable)—the relations of the general eye-movement factor to word reading and reading comprehension across various levels of reading proficiency (see Figs. 2 and 3).

One potential explanation for the stronger and robust relation between eye movements in the oral reading mode and reading proficiency is that it is an artifact of assessment method—for the word reading tasks, children were explicitly asked to read words aloud. However, if this was the case, the patterns of results should be different for word reading versus reading comprehension, with a stronger relation between eye movements and word reading as compared to that between eye movements and reading comprehension because for the reading comprehension tasks, children were not asked to read aloud. The results, however, showed very similar patterns, particularly in the fall: Correlations in the oral condition were −0.62 for word reading and −0.59 for reading comprehension, and correlations in the silent condition were −0.47 for word reading and −0.49 for reading comprehension. Moreover, if assessment method explains the current findings, the magnitudes of relations between eye movements and word reading should remain similar in the fall and spring. Results, however, showed a stronger relation in fall (−0.62) than in spring (−0.54).

An alternative explanation is that oral reading may be more conducive to focusing children's attention on printed words and self-monitoring compared to silent reading (Fuchs & Maxwell, 1988; Miller & Smith, 1985). Oral reading may also boost phonological coding by facilitating phonological information in working memory with extra feedback available during oral reading (Juel & Holmes, 1981; Kuhn, Schwanenflugel, & Meisinger, 2010). Although previous studies showed that novice readers or struggling readers benefited from oral reading compared to silent reading (Fuchs & Maxwell, 1988; Kragler, 1995; Prior & Welling, 2001), causal underlying mechanisms remain unclear and are beyond the scope of the present study. Regardless of causal mechanisms, our findings do indicate that children spend greater time looking at and revisiting words and also look at words more frequently during oral reading than during silent reading; in turn, more time and frequency of looking at words are positively related to reading proficiency as measured by word reading and reading comprehension.

One of the most striking findings in this study was that the relation of eye movements to children's reading skills varied as a function of

their reading proficiency. The overall relation between the latent, general eye-movement factor and reading proficiency was, on average, moderate such that higher reading proficiency was associated with less time on first fixation, rereading, and fewer regressions. However, eye movements were strongly related to word reading and reading comprehension for children with high reading proficiency whereas the relation was weak for children with low reading skills. The discrepancy in the magnitude of relations was particularly pronounced at the beginning of the school year (e.g., *rs* ranging from 0.05 to 0.77). In the spring, on the other hand, the relation of eye movements to reading stabilized for children at and above 0.30 quantile, with magnitudes of relations around 0.60 for word reading and 0.50 for reading comprehension in oral reading. These differential patterns between the beginning and the end of the year indicate that the relations between eye movements and reading proficiency are highly volatile[4] during the very beginning phase of reading development, followed by stabilization. Even in spring, for children below 0.30 quantile of reading proficiency, the relation remained weaker (see Figs. 2c and d and 3c and d). This weak relation could be interpreted in two ways: (a) children's poor reading skills result in relatively uncoordinated eye movements across the text (either having given up or trying to find something that can be understood) or (b) relatively unstructured eye movements result in poor reading. Following Blythe (2014), these two interpretations do not necessarily contradict each other, but are merely two sides of the same coin (also see Sperlich et al., 2016). Regardless of the nature of the relation, however, our findings demonstrate differential relations between eye movements and reading skills as a function of reading proficiency in developing readers. It is important to note again that the lack of a relationship between eye movements and reading proficiency in poorer readers was not simply a result of not reading the passage. Rather, all children tried to extract meaning with at least 100 fixations on words while reading each paragraph.

Although not our focal research question, findings from our exploration of factor structure of eye-movement variables for beginning readers are notable. Multiple eye-movement variables for beginning readers are best described as having a bi-factor structure with one common underlying factor (or the general eye-movement factor) and residual specific factors. The general eye-movement factor captures common shared variance among the various eye-movement variables and potentially the degree to which automatic processes aid visual information acquisition. As noted above, alternative models included one in which eye-movement variables were mapped onto different factors—early orthographic processing factor, lexical semantic processing factor, and higher order integration factor—based on theoretical models and empirical evidence from proficient adult readers. However, these models did not fit very well to our sample of beginning readers in Grade 1. Reasons for these results are unclear and beyond the scope of the present data; thus, future studies are necessary to explore this question further. We speculate, though, that the general eye-movement factor, rather than the three hypothesized factors, is likely to be related to the beginning phase of reading development in the participants. For beginning readers like those in the present study sample, various eye-movement behaviors may be highly constrained and characterized by decoding processes. In other words, decoding processes act as a bottleneck at the early stage of word reading, which may limit perceptual span (see, e.g., Sperlich et al., 2016) as well as higher order meaning-making processes. With further development in processes related to reading (e.g., phonological processing, grapheme-phoneme conversion) as well as in reading skills, meaning-making processes manifest their effects to a greater extent (e.g., Adlof, Catts, & Little, 2006; Kim, Wagner, & Lopez, 2012; Kim & Wagner, 2015). Then, various eye-movement behaviors should become less constrained by decoding processes, in which case multiple dimensions hypothesized from adult data (Radach et al., 2008; Radach & Kennedy, 2004; Rayner et al., 2006) might better represent eye movements. Interestingly, findings from studies using rapid automatized naming (RAN) show that performance in this task is a good indicator of later reading ability (e.g. Schatschneider, Fletcher, Francis, Carlson, & Foorman, 2004; Snowling, Gallagher, & Frith, 2003; Swanson, Trainin, Necoechea, & Hammill, 2003). Participants with better oculomotor control in RAN-like tasks were also better readers (Henry et al., 2018; Pan et al., 2013; Yan et al., 2013). Our general eye movement factor might capture similar processes related to oculomotor processing that are at work in RAN as well as reading. However, given the multitude of factors influencing RAN performance (as well as reading) and the fact that the exact mechanisms influencing RAN performance are still under debate, this idea should be treated with caution and needs further exploration.

Unfortunately, the present findings about dimensionality of various eye-movement variables and our speculations cannot be compared with other work, due to an absence of previous studies with adults or children. Thus, whether the above-noted theoretically based models fit data well for proficient readers or developing readers at a more advanced stage is an open question. It has been argued that the one-to-one mapping of eye-movement measures to certain processes might be an oversimplification (Kliegl & Laubrock, 2017). Future studies including longitudinal data with a longer time span (e.g., across elementary grades) would be informative about changes in eye-movement behaviors and their potentially changing dimensionality as children develop their reading skills.

## 7. Limitations and future directions

The present study was an initial step in an important line of work, investigating reading processes for beginning readers with an integrative approach. The findings are revealing, but also indicate a need for future studies to investigate several important questions. First, longer term longitudinal studies should investigate developmental patterns of eye movements during oral versus silent reading. Second, in the present study, we examined the relation of eye movements to reading proficiency using the general eye-movement factor based on our finding of a bi-factor structure for eye-movement indicators. As noted above, because determinacy scores were not appropriate, the residual, specific factors (e.g., rereading time) were not examined in relation to word reading and reading comprehension proficiency. Third, another direction for a future study with a larger sample size is to examine hypotheses related to eye movement, time, and modality interactions. Also unknown, yet highly important is when oral reading might cease to benefit reading development, and whether there is an optimal time for transitioning from oral to silent reading. Finally, it would be important to explore the causes of the weak relation between eye-movement measures and reading proficiency for novice readers. One reason to be examined here is the question about whether reading development stage in our sample were too initial to produce lexical-level effects in their eye movement measures (cf., Sperlich et al., 2016). Overall, the present findings underscore a need for developmental models of the eye-mind link, incorporating and accounting for developmental processes in reading.

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[4] It appears that the correlations between the general eye-movement factor and reading proficiency are stronger in fall than in spring for students with higher reading proficiency. Note that the number of students at the higher levels of performance is limited and therefore, estimates are not likely highly precise as indicated by large confidence intervals. Beyond this, theoretical explanations are unclear and future studies are needed.

## Appendix A. Eye-movement descriptive statistics by passage

See Tables A1–A4.

**Table A1**
Grade 1 fall oral reading descriptive statistics.

| Measure | *n* | *M* | *SD* | Minimum | Maximum |
|---|---|---|---|---|---|
| First Fixation Duration – Passage 1 | 277 | 351 | 71 | 225 | 597 |
| First Fixation Duration – Passage 2 | 250 | 363 | 79 | 220 | 737 |
| First Fixation Duration – Passage 3 | 214 | 344 | 78 | 200 | 723 |
| Initial Landing Position – Passage 1 | 277 | 1.85 | 0.23 | 1.18 | 2.99 |
| Initial Landing Position – Passage 2 | 250 | 1.91 | 0.25 | 1.33 | 2.59 |
| Initial Landing Position – Passage 3 | 214 | 2.01 | 0.27 | 1.24 | 2.75 |
| Refixation Duration – Passage 1 | 277 | 306 | 179 | 8 | 1004 |
| Refixation Duration – Passage 2 | 250 | 317 | 227 | 25 | 2064 |
| Refixation Duration – Passage 3 | 214 | 320 | 220 | 20 | 1690 |
| Number of Fixations in gaze – Passage 1 | 277 | 1.76 | 0.33 | 1.04 | 2.91 |
| Number of Fixations in gaze – Passage 2 | 250 | 1.76 | 0.37 | 1.14 | 3.93 |
| Number of Fixations in gaze – Passage 3 | 214 | 1.81 | 0.39 | 1.11 | 4.34 |
| Proportion of Refixations – Passage 1 | 277 | 0.41 | 0.10 | 0.06 | 0.65 |
| Proportion of Refixations – Passage 2 | 250 | 0.40 | 0.10 | 0.13 | 0.72 |
| Proportion of Refixations – Passage 3 | 214 | 0.42 | 0.11 | 0.09 | 0.73 |
| Rereading Time – Passage 1 | 277 | 730 | 899 | 32 | 11,973 |
| Rereading Time – Passage 2 | 250 | 653 | 585 | 23 | 3221 |
| Rereading Time – Passage 3 | 214 | 598 | 543 | 58 | 3261 |
| Rereading Time (gaze 2–6) – Passage 1 | 277 | 470 | 826 | 0 | 11,346 |
| Rereading Time (gaze 2–6) – Passage 2 | 250 | 425 | 638 | 0 | 6479 |
| Rereading Time (gaze 2–6) – Passage 3 | 214 | 361 | 463 | 7 | 2470 |
| Number of gazes on word – Passage 1 | 277 | 1.99 | 0.97 | 1.10 | 14.58 |
| Number of gazes on word – Passage 2 | 250 | 1.92 | 0.60 | 1.10 | 5.06 |
| Number of gazes on word – Passage 3 | 214 | 1.83 | 0.54 | 1.19 | 4.81 |
| Proportion of Regressions – Passage 1 | 277 | 0.31 | 0.06 | 0.15 | 0.62 |
| Proportion of Regressions – Passage 2 | 250 | 0.31 | 0.06 | 0.15 | 0.47 |
| Proportion of Regressions – Passage 3 | 214 | 0.31 | 0.06 | 0.18 | 0.54 |
| Refixation Duration (gaze 2–6) – Passage 1 | 277 | 291 | 248 | 14 | 2242 |
| Refixation Duration (gaze 2–6) – Passage 2 | 250 | 273 | 230 | 9 | 1760 |
| Refixation Duration (gaze 2–6) – Passage 3 | 214 | 294 | 261 | 3 | 1521 |

*Note*. Times and durations are presented in ms, and landing position is presented in character spaces.

**Table A2**
Grade 1 spring oral reading descriptive statistics.

| Measure | *n* | *M* | *SD* | Minimum | Maximum |
|---|---|---|---|---|---|
| First Fixation Duration – Passage 1 | 343 | 335 | 71 | 114 | 638 |
| First Fixation Duration – Passage 2 | 339 | 346 | 73 | 119 | 699 |
| First Fixation Duration – Passage 3 | 325 | 344 | 76 | 103 | 680 |
| Initial Landing Position – Passage 1 | 343 | 1.93 | 0.21 | 1.20 | 2.56 |
| Initial Landing Position – Passage 2 | 339 | 1.93 | 0.21 | 1.23 | 2.45 |
| Initial Landing Position – Passage 3 | 325 | 1.91 | 0.21 | 1.37 | 2.60 |
| Refixation Duration – Passage 1 | 343 | 212 | 123 | 24 | 756 |
| Refixation Duration – Passage 2 | 339 | 208 | 118 | 38 | 712 |
| Refixation Duration – Passage 3 | 325 | 248 | 137 | 49 | 914 |
| Number of Fixations in gaze – Passage 1 | 343 | 1.61 | 0.26 | 1.11 | 2.52 |
| Number of Fixations in gaze – Passage 2 | 339 | 1.58 | 0.26 | 1.19 | 2.85 |
| Number of Fixations in gaze – Passage 3 | 325 | 1.67 | 0.28 | 1.17 | 3.12 |
| Proportion of Refixations – Passage 1 | 343 | 0.35 | 0.09 | 0.11 | 0.58 |
| Proportion of Refixations – Passage 2 | 339 | 0.34 | 0.09 | 0.14 | 0.63 |
| Proportion of Refixations – Passage 3 | 325 | 0.38 | 0.09 | 0.13 | 0.65 |
| Rereading Time – Passage 1 | 343 | 371 | 296 | 42 | 2029 |
| Rereading Time – Passage 2 | 339 | 396 | 304 | 52 | 1945 |
| Rereading Time – Passage 3 | 325 | 424 | 299 | 38 | 1715 |
| Rereading Time (gaze 2–6) – Passage 1 | 343 | 253 | 363 | 0 | 2776 |
| Rereading Time (gaze 2–6) – Passage 2 | 339 | 225 | 276 | 0 | 2800 |
| Rereading Time (gaze 2–6) – Passage 3 | 325 | 299 | 358 | 5 | 3968 |
| Number of gazes on word – Passage 1 | 343 | 1.67 | 0.38 | 1.14 | 4.50 |
| Number of gazes on word – Passage 2 | 339 | 1.73 | 0.39 | 1.17 | 3.82 |
| Number of gazes on word – Passage 3 | 325 | 1.70 | 0.36 | 1.14 | 3.54 |
| Proportion of Regressions – Passage 1 | 343 | 0.29 | 0.06 | 0.14 | 0.46 |
| Proportion of Regressions – Passage 2 | 339 | 0.29 | 0.05 | 0.16 | 0.47 |
| Proportion of Regressions – Passage 3 | 325 | 0.29 | 0.06 | 0.15 | 0.47 |
| Refixation Duration (gaze 2–6) – Passage 1 | 343 | 181 | 225 | 11 | 3081 |
| Refixation Duration (gaze 2–6) – Passage 2 | 339 | 162 | 118 | 8 | 847 |
| Refixation Duration (gaze 2–6) – Passage 3 | 325 | 220 | 150 | 17 | 1186 |

*Note*. Times and durations are presented in ms, and landing position is presented in character spaces.

**Table A3**
Grade 2 fall silent reading descriptive statistics.

| Measure | *n* | *M* | *SD* | Minimum | Maximum |
|---|---|---|---|---|---|
| First Fixation Duration – Passage 1 | 248 | 333 | 71 | 185 | 603 |
| First Fixation Duration – Passage 2 | 229 | 341 | 79 | 190 | 686 |
| First Fixation Duration – Passage 3 | 195 | 335 | 74 | 186 | 718 |
| Initial Landing Position – Passage 1 | 248 | 2.00 | 0.28 | 1.18 | 3.02 |
| Initial Landing Position – Passage 2 | 229 | 2.03 | 0.27 | 1.19 | 2.92 |
| Initial Landing Position – Passage 3 | 195 | 2.16 | 0.30 | 1.45 | 3.12 |
| Refixation Duration – Passage 1 | 248 | 223 | 151 | 22 | 1419 |
| Refixation Duration – Passage 2 | 229 | 221 | 139 | 28 | 848 |
| Refixation Duration – Passage 3 | 195 | 224 | 140 | 41 | 874 |
| Number of Fixations in gaze – Passage 1 | 248 | 1.60 | 0.29 | 1.08 | 3.03 |
| Number of Fixations in gaze – Passage 2 | 229 | 1.58 | 0.26 | 1.13 | 2.88 |
| Number of Fixations in gaze – Passage 3 | 195 | 1.62 | 0.28 | 1.16 | 2.72 |
| Proportion of Refixations – Passage 1 | 248 | 0.35 | 0.10 | 0.11 | 0.63 |
| Proportion of Refixations – Passage 2 | 229 | 0.34 | 0.09 | 0.11 | 0.62 |
| Proportion of Refixations – Passage 3 | 195 | 0.36 | 0.10 | 0.12 | 0.60 |
| Rereading Time – Passage 1 | 248 | 388 | 340 | 35 | 2202 |
| Rereading Time – Passage 2 | 229 | 390 | 404 | 54 | 2928 |
| Rereading Time – Passage 3 | 195 | 351 | 329 | 23 | 2450 |
| Rereading Time (gaze 2–6) – Passage 1 | 248 | 243 | 266 | 0 | 1727 |
| Rereading Time (gaze 2–6) – Passage 2 | 230 | 300 | 604 | 0 | 7248 |
| Rereading Time (gaze 2–6) – Passage 3 | 196 | 222 | 287 | 0 | 2151 |
| Number of gazes on word – Passage 1 | 248 | 1.65 | 0.39 | 1.12 | 3.32 |
| Number of gazes on word – Passage 2 | 229 | 1.65 | 0.44 | 1.16 | 4.31 |
| Number of gazes on word – Passage 3 | 195 | 1.58 | 0.33 | 1.11 | 3.51 |
| Proportion of Regressions – Passage 1 | 248 | 0.31 | 0.07 | 0.15 | 0.50 |
| Proportion of Regressions – Passage 2 | 229 | 0.30 | 0.07 | 0.15 | 0.51 |
| Proportion of Regressions – Passage 3 | 195 | 0.30 | 0.06 | 0.15 | 0.50 |
| Refixation Duration (gaze 2–6) – Passage 1 | 248 | 221 | 196 | 7 | 1272 |
| Refixation Duration (gaze 2–6) – Passage 2 | 229 | 195 | 187 | 6 | 1330 |
| Refixation Duration (gaze 2–6) – Passage 3 | 195 | 199 | 170 | 0 | 1293 |

*Note*. Times and durations are presented in ms, and landing position is presented in character spaces.

**Table A4**
Grade 2 spring silent reading descriptive statistics.

| Measure | *n* | *M* | *SD* | Minimum | Maximum |
|---|---|---|---|---|---|
| First Fixation Duration – Passage 1 | 316 | 313 | 61 | 174 | 482 |
| First Fixation Duration – Passage 2 | 300 | 322 | 66 | 189 | 577 |
| First Fixation Duration – Passage 3 | 278 | 319 | 64 | 190 | 604 |
| Initial Landing Position – Passage 1 | 316 | 2.01 | 0.25 | 1.23 | 2.74 |
| Initial Landing Position – Passage 2 | 300 | 1.98 | 0.23 | 1.38 | 2.54 |
| Initial Landing Position – Passage 3 | 278 | 1.98 | 0.26 | 1.36 | 2.65 |
| Refixation Duration – Passage 1 | 316 | 17 | 105 | 18 | 677 |
| Refixation Duration – Passage 2 | 300 | 168 | 96 | 16 | 633 |
| Refixation Duration – Passage 3 | 278 | 199 | 117 | 23 | 771 |
| Number of Fixations in gaze – Passage 1 | 316 | 1.52 | 0.24 | 1.08 | 2.63 |
| Number of Fixations in gaze – Passage 2 | 300 | 1.49 | 0.21 | 1.06 | 2.57 |
| Number of Fixations in gaze – Passage 3 | 278 | 1.58 | 0.25 | 1.10 | 2.43 |
| Proportion of Refixations – Passage 1 | 316 | 0.32 | 0.09 | 0.08 | 0.58 |
| Proportion of Refixations – Passage 2 | 300 | 0.31 | 0.08 | 0.07 | 0.58 |
| Proportion of Refixations – Passage 3 | 278 | 0.34 | 0.09 | 0.10 | 0.58 |
| Rereading Time – Passage 1 | 316 | 258 | 220 | 11 | 1656 |
| Rereading Time – Passage 2 | 300 | 271 | 211 | 3 | 1938 |
| Rereading Time – Passage 3 | 278 | 280 | 212 | 3 | 1414 |
| Rereading Time (gaze 2–6) – Passage 1 | 316 | 176 | 240 | 0 | 2070 |
| Rereading Time (gaze 2–6) – Passage 2 | 300 | 154 | 164 | 0 | 1192 |
| Rereading Time (gaze 2–6) – Passage 3 | 279 | 200 | 230 | 0 | 1535 |
| Number of gazes on word – Passage 1 | 316 | 1.52 | 0.31 | 1.05 | 3.28 |
| Number of gazes on word – Passage 2 | 300 | 1.56 | 0.32 | 1.01 | 3.95 |
| Number of gazes on word – Passage 3 | 278 | 1.53 | 0.28 | 1.02 | 3.13 |
| Proportion of Regressions – Passage 1 | 316 | 0.29 | 0.06 | 0.08 | 0.56 |
| Proportion of Regressions – Passage 2 | 300 | 0.28 | 0.06 | 0.13 | 0.50 |
| Proportion of Regressions – Passage 3 | 278 | 0.28 | 0.05 | 0.12 | 0.43 |
| Refixation Duration (gaze 2–6) – Passage 1 | 316 | 144 | 111 | 0 | 809 |
| Refixation Duration (gaze 2–6) – Passage 2 | 300 | 132 | 105 | 0 | 630 |
| Refixation Duration (gaze 2–6) – Passage 3 | 278 | 191 | 204 | 0 | 1865 |

*Note*. Times and durations are presented in ms, and landing position is presented in character spaces.

## Appendix B. Examination of oral and silent reading order

See Tables B1 and B2.

**Table B1**
Means and standard deviations for repeated measures ANOVA on reading mode (within-subject) and order effects (between-subjects) for wave 1.

| | Silent reading first | | | | Oral reading first | | | |
|---|---|---|---|---|---|---|---|---|
| | Silent | | Oral | | Silent | | Oral | |
| Measures | Mean | SD | Mean | SD | Mean | SD | Mean | SD |
| First Fixation Duration | 338 | 72 | 354 | 69 | 330 | 67 | 346 | 66 |
| Refixation Duration | 233 | 141 | 310 | 212 | 200 | 117 | 307 | 169 |
| Rereading Time | 408 | 378 | 633 | 532 | 337 | 320 | 677 | 598 |
| Number of Fixations in Gaze | 1.60 | 0.25 | 1.77 | 0.35 | 1.57 | 0.23 | 1.79 | 0.33 |
| Number of Gazes on Word | 1.66 | 0.38 | 1.89 | 0.54 | 1.59 | 0.37 | 1.96 | 0.67 |
| Proportion of Refixations | 0.36 | 0.09 | 0.41 | 0.10 | 0.34 | 0.09 | 0.41 | 0.10 |
| Proportion of Regressions | 0.32 | 0.07 | 0.31 | 0.06 | 0.29 | 0.06 | 0.31 | 0.06 |
| Initial Landing Position | 2.07 | 0.27 | 1.91 | 0.23 | 2.06 | 0.22 | 1.90 | 0.21 |

**Table B2**
F and p values for repeated measures ANOVA on reading mode (within-subject) and order effects (between-subjects) for wave 1.

| | Reading mode | | Condition order | | Reading mode × Condition order | |
|---|---|---|---|---|---|---|
| Measure | $F_{(1,211)}$ | $p$ | $F_{(1,211)}$ | $p$ | $F_{(1,211)}$ | $p$ |
| First Fixation Duration | 19.69 | < 0.001 | *0.789* | 0.38 | 0.002 | 0.967 |
| Refixation Duration | 79.98 | < 0.001 | 0.867 | 0.353 | 2.255 | 0.135 |
| Rereading Time | 74.15 | < 0.001 | 0.060 | 0.806 | 3.086 | 0.080 |
| Number of Fixations in Gaze | 86.48 | < 0.001 | 0.064 | 0.801 | 2.121 | 0.147 |
| Number of Gazes on Word | 62.77 | < 0.001 | 0.004 | 0.952 | 3.757 | 0.054 |
| Proportion of Refixations | 105.73 | < 0.001 | 0.144 | 0.704 | 2.654 | 0.105 |
| Proportion of Regressions | 0.33 | 0.568 | 1.825 | 0.178 | *13.957* | *< 0.001* |
| Initial Landing Position | 69.17 | < 0.001 | 0.327 | 0.568 | 0.029 | 0.865 |

## Appendix C. Factor analysis of eye-movement variables

As we noted in the data analysis section, factor analysis was used to model the variance-covariance matrix of the eye-tracking indexes in order to leverage the common variance across indexes in estimating more precise estimates of the underlying cognitive processes. A well-known limitation of manifest variables via classical test theory is that measurements of behavior are not error free and limit the reliability and precision of what a researcher is estimating (Nunnally & Bernstein, 1994). The common variance across measures can be formed into a latent variable thereby improving reliability of measurement (Kline, 2013).

In the present study, three confirmatory factor models were tested using the indices listed in Table A1: (a) a three-factor model of orthographic processing, lexical semantic processing, and integration (Model 1), (b) a one-factor model consisting of all indices in Table A1 (Model 2), and (c) a second-order factor model where index-level factors were created with orthographic processing, lexical semantic processing, and integration factors (Model 3). Model fit from Model 1 at the fall and spring time points for silent and oral reading was extremely poor [i.e., Fall Silent: $\chi^2(321) = 3774.54$, CFI = 0.59, TLI = 0.55, RMSEA = 0.21; Fall Oral: $\chi^2(321) = 4344.03$, CFI = 0.61, TLI = 0.58, RMSEA = 0.21; Spring Silent: $\chi^2(321) = 3689.97$, CFI = 0.65, TLI = 0.62, RMSEA = 0.18; Spring Oral: $\chi^2(321) = 4252.97$, CFI = 0.66, TLI = 0.62, RMSEA = 0.19], suggesting that the hypothesized model did not translate well to the present sample. The unidimensional model (Model 2) also failed to provide acceptable fit to the data at either the fall or spring time point for the silent and oral reading processes [i.e., Fall Silent: $\chi^2(324) = 5461.46$, CFI = 0.39, TLI = 0.34, RMSEA = 0.25; Fall Oral: $\chi^2(324) = 6823.93$, CFI = 0.37, TLI = 0.32, RMSEA = 0.27; Spring Silent: $\chi^2(324) = 5040.67$, CFI = 0.52, TLI = 0.48, RMSEA = 0.22; Spring Oral: $\chi^2(324) = 6758.97$, CFI = 0.44, TLI = 0.39, RMSEA = 0.24]. Similarly, Model 3 failed to provide acceptable fit to the data [i.e., Fall Silent: $\chi^2(324) = 3792.82$, CFI = 0.59 TLI = 0.55, RMSEA = 0.21; Fall Oral: $\chi^2(324) = 4002.64$, CFI = 0.65, TLI = 0.62, RMSEA = 0.20; Spring Silent: $\chi^2(324) = 4772.40$, CFI = 0.54, TLI = 0.51, RMSEA = 0.21; Spring Oral: $\chi^2(324) = 5212.16$, CFI = 0.57, TLI = 0.54, RMSEA = 0.21].

The lack of acceptable model fit for any of the theoretically driven models led to the specification of exploratory factor analyses (EFAs) using the same indexes to identify the extent to which a simple solution with acceptable fit and theoretically meaningful relations could be established. The result showed that only one model provided overall reasonable fit to the data, $\chi^2$ (144) = 596.85, CFI = 0.96, TLI = 0.89, RMSEA = 0.11 for Fall Oral: a 10-factor model that was inclusive of index-specific factors, passage-specific factors, and a global factor (i.e., Factor 1 = First Fixation Duration factor, Factor 2 = Refixation Duration factor, Factor 3 = Passage 1 index factor, Factor 4 = Passages 2 and 3 index factor, Factor 5 = Rereading Time (gaze 2–6) factor, Factor 6 = Proportion of Regressions index factor, Factor 7 = Passage 3 index factor, Factor 8 = Passage 2 index factor, Factor 9 = Passage 1 index factor, and Factor 10 = General Factor of Eye Movements). Despite the model fit that maintained elements that conformed to statistical guidelines (i.e., acceptable CFI), there was no viable theoretical framework that could explain this specific finding. Notwithstanding this limitation, the EFA results revealed two patterns that were useful in constructing an alternative, confirmatory structure. First, several of the factors in the 10-factor solution were reflective of index-based groupings whereby the largest loadings were for indexes *across* passages

(e.g., creating a refixation duration factor that was indicated by refixation duration at each of the passages 1–3), similar to the groupings that were tested in Models 1 and 3. Second, several of the factors were predominantly indicated by passage-based groupings whereby the largest loadings were for multiple indices *within* passages (e.g., creating a passage 2 factor for fixation count, proportion of refixations, and gaze duration for paragraph 2). These two patterns led to the specification of a bi-factor model in order to test for the presence of index-specific factors, paragraph-specific factors, and then a general factor of eye movements. Bi-factors have been found to be useful in understanding data structures where there are either theoretical or observed strong relations among what is being measured (Kim, Park, & Park, 2015; Kieffer et al., 2016; Reise, 2012). Because multiple indices are expected to correlate with each other due to unique, yet overlapping measurement of underlying cognitive processes associated with beginning reading, the bi-factor model can flexibly estimate the presence of theoretically meaningful factors as well as specific, residual factors that may be attributed to phenomena that are related to each other (i.e., refixation duration, rereading time; see Fig. 1) but unrelated to the theoretical construct of interest.

## Appendix D. Standardized loadings for each measurement occasion by reading mode

See Tables D1 and D2.

**Table D1**
Standardized loadings for fall and spring oral reading.

| | Fall oral reading | | | | | | | Spring oral reading | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Measure | GEM | SF | LP | EP | P1 | P2 | P3 | GEM | SF | LP | EP | P1 | P2 | P3 |
| Initial landing position P1 | −0.47 | 0.48 | | | −0.24 | | | −0.48 | 0.53 | | | −0.27 | | |
| Initial landing position P2 | −0.54 | 0.65 | | | | 0.19 | | −0.37 | 0.64 | | | | −0.29 | |
| Initial landing position P3 | −0.58 | 0.46 | | | | | −0.15 | −0.48 | 0.42 | | | | | −0.37 |
| Number of fixations in gaze P1 | 0.78 | | | | 0.62 | | | 0.51 | | | | 0.84 | | |
| Number of fixations in gaze P2 | 0.75 | | | | | −0.67 | | 0.46 | | | | | 0.89 | |
| Number of fixations in gaze P3 | 0.83 | | | | | | 0.56 | 0.48 | | | | | | 0.86 |
| Proportion of refixations P1 | 0.88 | | | | 0.31 | | | 0.57 | | | | 0.79 | | |
| Proportion of refixations P2 | 0.83 | | | | | −0.41 | | 0.51 | | | | | 0.79 | |
| Proportion of refixations P3 | 0.85 | | | | | | | 0.56 | | | | | | 0.78 |
| Rereading duration P1 | 0.63 | | 0.38 | | | | | 0.54 | | 0.29 | | | | |
| Rereading duration P2 | 0.73 | | 0.30 | | | | | 0.69 | | 0.51 | | | | |
| Rereading duration P3 | 0.72 | | 0.38 | | | | | 0.59 | | 0.38 | | | | |
| Number of gazes per word P1 | 0.28 | | 0.68 | | | | | 0.34 | | 0.81 | | | | |
| Number of gazes per word P2 | 0.57 | | 0.79 | | | 0.22 | | 0.30 | | 0.88 | | | | |
| Number of gazes per word P3 | 0.45 | | 0.78 | | | | | 0.32 | | 0.88 | | | | |
| Refixation duration P2 | 0.77 | | | | | −0.53 | | 0.81 | | | | | 0.53 | |
| Refixation duration P3 | 0.86 | | | | | | | 0.84 | | | | | | 0.47 |
| First fixation duration P1 | 0.46 | | | 0.79 | | | | 0.73 | | | 0.53 | | | |
| First fixation duration P2 | 0.46 | | | 0.79 | | | | 0.79 | | | 0.52 | | | |
| First fixation duration P3 | 0.51 | | | 0.75 | | | | 0.79 | | | 0.49 | | | |

*Note*. GEM = general eye-movement factor; SF = spatial factor; LP = later processing; EP = early processing; P1 = Passage 1; P2 = Passage 2; P3 = Passage 3.

**Table D2**
Standardized loadings for fall and spring silent reading.

| | Fall silent reading | | | | | | | Spring silent reading | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Measure | GEM | SF | LP | EP | P1 | P2 | P3 | GEM | SF | LP | EP | P1 | P2 | P3 |
| Initial landing position P1 | −0.40 | 0.55 | | | −0.32 | | | −0.40 | 0.49 | | | −0.39 | | |
| Initial landing position P2 | −0.29 | 0.68 | | | | 0.41 | | −0.42 | 0.49 | | | | −0.33 | |
| Initial landing position P3 | −0.29 | 0.42 | | | | | −0.54 | −0.49 | 0.55 | | | | | −0.31 |
| Number of fixations in gaze P1 | 0.58 | | | | 0.82 | | | 0.56 | | | | 0.80 | | |
| Number of fixations in gaze P2 | 0.55 | | | | | −0.83 | | 0.61 | | | | | 0.80 | |
| Number of fixations in gaze P3 | 0.45 | | | | | | 0.89 | 0.59 | | | | | | 0.77 |
| Proportion of refixations P1 | 0.62 | | | | 0.68 | | | 0.59 | | | | 0.77 | | |
| Proportion of refixations P2 | 0.62 | | | | | −0.70 | | 0.58 | | | | | 0.75 | |
| Proportion of refixations P3 | 0.54 | | | | | | | 0.61 | | | | | | 0.77 |
| Rereading duration P1 | 0.64 | | 0.22 | | | | | 0.54 | | 0.45 | | | | |
| Rereading duration P2 | 0.67 | | 0.33 | | | | | 0.62 | | 0.44 | | | | |
| Rereading duration P3 | 0.68 | | 0.24 | | | | | 0.66 | | 0.41 | | | | |
| Number of gazes per word P1 | 0.37 | | 0.68 | | | | | 0.32 | | 0.78 | | | | |
| Number of gazes per word P2 | 0.49 | | 0.87 | | | 0.10 | | 0.35 | | 0.74 | | | | |
| Number of gazes per word P3 | 0.48 | | 0.70 | | | | | 0.33 | | 0.82 | | | | |

(*continued on next page*)

**Table D2** (*continued*)

| Measure | Fall silent reading | | | | | | | Spring silent reading | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | GEM | SF | LP | EP | P1 | P2 | P3 | GEM | SF | LP | EP | P1 | P2 | P3 |
| Refixation duration P2 | 0.80 | | | | | −0.55 | | 0.85 | | | | | 0.49 | |
| Refixation duration P3 | 0.70 | | | | | | | 0.83 | | | | | | 0.49 |
| First fixation duration P1 | 0.72 | | | 0.54 | | | | 0.74 | | | −0.54 | | | |
| First fixation duration P2 | 0.72 | | | 0.58 | | | | 0.79 | | | −0.49 | | | |
| First fixation duration P3 | 0.75 | | | 0.49 | | | | 0.80 | | | −0.47 | | | |

*Note*. GEM = general eye-movement factor; SF = spatial factor; LP = later processing; EP = early processing; P1 = Passage 1; P2 = Passage 2; P3 = Passage.

## Appendix E. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.cedpsych.2019.03.002.

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