7-28-2023

The Relation of Oral and Silent Reading with Reading Comprehension Through the Use of Eye-Tracking

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THE RELATION OF ORAL AND SILENT READING WITH READING COMPREHENSION THROUGH THE USE OF EYE-TRACKING

by

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A Dissertation

Submitted in Partial Fulfillment of the

Requirements for the Degree of

Doctor of Philosophy

Major: School Psychology

The University of Memphis

August 2023

Abstract

Although eye-tracking measures demonstrate the ability to provide unique contributions to reading research, use of these tools among child populations remains sparse and only one other study has explored the role of reading modality on eye movement behaviors among developing readers using structural equation modeling (SEM) techniques. To address these concerns, this study utilized an eye-tracking tool to examine reading fluency and comprehension skills during oral and silent reading among 490 students in fourth and fifth grade. ANOVAs were used to examine grade and modality differences in eye movement behaviors. Grade level and reading modality significantly impacted participants' rereading duration, number of gazes per word, and probability of committing interword regressions. Specifically, during silent reading, fourth graders exhibited fewer gazes per word compared to students in fifth grade. Shorter rereading durations were found among fifth graders when reading silently whereas they engaged in more interword regressions during oral reading. SEM analytic approaches were used to examine the factor structure of eye movements, which yielded a unidimensional latent factor in this sample consisting of single-fixation duration, first-fixation duration, and rereading duration. To better understand reading development, further studies should consider the factor structure of eye movements during oral and silent reading, and how these processes impact reading comprehension skills.

Table of Contents

Tables

The Relation of Oral and Silent Reading with Reading Comprehension Through the Use of Eye-Tracking

Reading modality is understood as the difference between oral versus silent reading methods (Prior & Welling, 2001). During the early elementary years, oral reading is widely acknowledged to be beneficial for beginning readers, whereas students in late elementary school and beyond engage predominantly in silent reading (Hiebert et al., 2012; Kuhn & Schwanenflugel, 2007; Robinson et al., 2018). Indeed, the expectation of a skilled reader is one who can read silently with comprehension (Share, 2008). Despite our understanding of the importance of oral and silent reading to overall reading competence, few studies have focused on the differences and similarities between reading modalities (Price et al., 2015). To understand underlying cognitive processes critical for reading, a growing amount of focus has been allocated to eye-tracking studies. However, much of this work has been devoted to adult readers, leaving a lack of knowledge about developmental changes related to reading acquisition in children (Kim et al., 2019).

The aim of this study is to understand the similarities and differences in oral versus silent reading, and how modality relates to reading comprehension skills during the late elementary school years. First, the literature comparing the oral versus silent reading modalities will be reviewed, with an emphasis on developmental differences across grade levels. Within this realm, the comparative effects of reading modality on comprehension skills will be investigated. Eye-tracking as a measure of oral and silent reading development will also be introduced, with a focus on specific cognitive and reading processes. Further, studies incorporating eye-tracking as a measure of oral and silent reading in developing readers are summarized, and examinations of reading modality effects on comprehension within the eye-tracking literature will be reviewed. Finally, the aims of the current study are discussed, with a focus on the exploration and comparison of factor structures of reading skills and eye movement behaviors among fourth and fifth graders.

Reading Fluency Skill Development

It is widely understood that oral reading fluency is a combination of accuracy, automaticity, and prosody, all of which assist with the construction of meaning from text (Kuhn et al., 2010). Consistent with Chall's (1983, 1996) stage theory of reading development, most students develop fluent oral reading abilities during the fluency stage in second and third grade. Early learners are primarily instructed to read aloud, as this modality allows for the understanding of letter-sound correspondence, application of listening comprehension skills, and can be corrected and monitored by teachers for early intervention (Schwanenflugel & Knapp, 2016; Robinson & Meisinger, 2021). Oral reading is also thought to serve as a phonological memory code relevant for text comprehension, as students are able to control reading pace while reading aloud to support comprehension skills (Robinson & Meisinger, 2021; Schwanenflugel & Knapp, 2016). By the fourth grade, school curriculum transitions from teaching students how to read orally to reading silently (Chall, 1983, 1996). Notably, although much is known about oral reading, silent reading processing has been generally overlooked in research (Hiebert & Reutzel, 2010; Share, 2008).

There is consensus in the literature that a significant relation exists between oral reading fluency and reading comprehension, spanning multiple grade levels (Chard et al., 2002; Kuhn & Schwanenflugel, 2007; National Reading Panel, 2000; Sabatini et al., 2019; Turkyılmaz et al., 2014; Wang, 2020; White et al., 2021). Due to the importance of automaticity of reading skills to comprehension processing, reading fluency has been repeatedly described as the bridge to reading comprehension (Pikulski & Chard, 2005). However, the robust correlation between oral reading fluency and comprehension weakens as readers develop more advanced reading skills (Wayman et al., 2007). This is not surprising given that children are expected to transition from oral to silent reading once they are in the fourth grade or late elementary school (Chall, 1983, 1996), and this switch is often accompanied by greater reading speed and more advanced comprehension skills.

Silent reading with comprehension is frequently viewed as the benchmark for literacy (Lundberg, 1994; Share, 2008; Torgesen, 2005). As readers become more proficient across development, the utility of oral reading declines, as it is considered a distraction or even hinderance to comprehension due to the use of cognitive resources needed for pronunciation and expression (Prior et al., 2011; Robinson et al., 2018; Vorstius et al., 2014). Furthermore, silent reading is associated with efficient and flexible use of cognitive resources, allowing for more strategic reading behaviors. Due to limitations associated with eye-voice coordination and monitoring of articulation and speech, oral reading often suppresses the reading regressions characteristic to silent reading, such as rereading a difficult word or sentence (Inhoff et al., 2004, 2011). By sixth or seventh grade, it is understood that oral reading rates for skilled readers plateau at about 150 to 175 words per minute due to constraints from speech production speed, whereas silent reading rates can develop through college (Hausbrouck & Tindal, 2006; Hiebert et al., 2010).

Despite the known benefits of silent reading for comprehension among skilled readers, there is a lack of knowledge about the shift from oral to silent reading (Hiebert & Reutzel, 2010). Oral reading is known to facilitate the transition from oral to silent reading, as it is involved in the internalization of cognitive processes needed for reading (Prior et al., 2011; Schwanenflugel & Knapp, 2016). Throughout elementary school and beyond, students begin to adopt silent reading as text becomes more difficult, and this necessitates the use of prior background knowledge and higher-level cognitive abilities, including summarization and inferencing (Sweet & Snow, 2003). Next, given that oral reading speed relies on individual speech, rate carries a different role within both modalities (Hiebert et al., 2010). Per Share (2008), due to the understanding that oral reading depends more on phonological processing, this modality is associated with typically slower reading rates. Furthermore, once silent reading skills are achieved, processing rates associated with silent reading may signal more efficient processing, yielding more cognitive resources for comprehension processing (Robinson et al., 2018).

In addition to its clear impact on reading comprehension, oral reading has also been viewed as the gateway to silent reading skill development, a crucial skill as students begin to interact with more complex text. Vygotsky's (1978) theory of speech development has been used as a framework to conceptualize the transition from oral to silent reading (Kragler, 1995; Miller & Smith, 1990; Prior et al., 2011; Prior & Welling, 2001; Wilkinson & Anderson, 1995). Parallel to speech development, this theory proposes that reading has social origins, as children often listen to others read to them, which is followed by a transitional stage that is characterized by children reading aloud to themselves just as others had read to them. Within this phase, listening to parents and teachers read also allows for scaffolded support as independent reading skills develop, as students can attend to relations between individual words and their roles in the overall passage. In the final stage of Vygotsky's theory, children can adequately internalize reading, or read in their heads. Consistent with findings by Prior et al. (2011), oral reading becomes less advantageous when readers accomplish silent reading, as reading silently does not require attention to phonetics and unnecessary words, and this designates silent reading as the ideal mode for comprehension. Lastly, in accordance with Vygotsky's framework, it is not uncommon for beginning silent readers to still demonstrate higher comprehension performance after reading orally, as students are still learning independent reading and may therefore require more silent reading practice.

Comparing Modality Impacts on Reading Comprehension

Among the studies that have examined the impact of modality on reading comprehension, participants are often asked to read passages orally and silently, and performances on comprehension tasks are then compared (Dickens & Meisinger, 2015, 2016; Prior et al., 2001, 2011; Schimmel & Ness, 2017). Results generally imply that early elementary students can better comprehend text after oral reading rather than after listening or reading silently to themselves (Elgart, 1978; Fletcher & Pumfrey, 1988; Kragler, 1995). For example, after Prior et al. (2011) investigated the relation of reading modality with comprehension among students between first and seventh grade, findings supported higher comprehension skills among first through fifth graders, and equal comprehension across silent and oral reading modalities among sixth graders. However, students in seventh grade demonstrated significantly higher comprehension abilities when they read silently, illustrating the importance of silent reading among students in later grades (Prior et al., 2011). Despite this importance, relatively few studies have examined differences in reading comprehension between oral and silent reading modalities, especially among a broad range of grade levels (Hale et al., 2007; Prior & Welling, 2001; Prior et al., 2011). While theories of reading comprehension often acknowledge the multidimensionality of the construct, most standardized tests of comprehension still treat it as a unitary construct, despite some key studies providing evidence to the contrary (Keenan et al., 2008; Cutting et al., 2006). In their study aiming to determine differences among five commonly used reading comprehension measures with participants ages eight to 18, Keenan et al. (2008) found that individual differences in reading development predicted comprehension performance. Relatedly, reading comprehension measures may vary based on how much they tap reading comprehension versus decoding skills (Collins et al., 2018; Keenan et al., 2008). Examination of intercorrelations between the five assessments suggested little evidence that the measures are similar to one another, and should not be used interchangeably (Keenan et al., 2008). Additionally, in their reading comprehension study with fourth-grade students who had diverse profiles of language skills, Collins et al. (2021) found that external factors such as varying item response formats and text genre predicted differences in scores after relying on only one standardized measure, suggesting that multiple measures should be used when assessing students' reading comprehension skills.

To date, a few studies have used structural equation modeling (SEM) analyses to better understand the relations among oral and silent reading fluency with comprehension (Kim et al., 2011; Price et al., 2016; Turkyılmaz et al., 2014; Robinson & Meisinger, 2021). Kim et al. (2011) used latent variables to assess the predictability of oral and silent reading fluency on comprehension of passages among average and advanced first-grade readers. Results indicated that oral reading fluency better predicted reading comprehension compared to silent reading fluency, with decoding fluency being the most significant predictor of comprehension and oral and silent reading. Next, in their study with fourth-grade readers, Price et al. (2015) examined oral and silent reading modes as separate constructs using SEM models. Parallel to previous findings, they concluded that only oral reading fluency and oral vocabulary skills significantly predicted reading comprehension. Similarly, Turkyılmaz et al. (2014) examined indicators of reading comprehension skills with the inclusion of retell fluency among Turkish students in the fifth grade. All predictors of reading comprehension, including oral and silent reading fluency, as well as retell fluency, were highly and positively related in the model, with oral reading fluency being the most predictive of comprehension skills. Finally, Robinson and Meisinger (2021) studied readers with dyslexia in second through fifth grade across a school year (fall to spring) and found that oral reading fluency explained unique variance in silent and oral reading comprehension, but that silent reading fluency did not contribute to reading comprehension in either modality after students were asked to orally recall a passage. Together, these results suggest that oral reading fluency plays a unique role in supporting comprehension skills, which aligns with existing support that silent and oral reading fluency can be thought of as separate but related constructs (Kim et al., 2011; Price et al., 2016; Robinson & Meisinger, 2021).

Eye-tracking research has consistently demonstrated that readers' eyes are often ahead of the voice, and this supports the need for greater attention towards measures of silent reading (Radach et al., 2009; Rayner & Pollatsek, 1989). In school settings, curriculum-based measures of oral reading fluency (CBM-R) are commonly used assessments that are quick, easy to implement, and enjoy adequate psychometric properties (Foster et al., 2018; Reschly et al., 2009; Wayman et al., 2007). Eye-tracking is the gold standard for assessing silent reading behavior, but until recently, this technology required large equipment that was not easily transportable, and this made it unsuitable for large-scale data collections in school settings. Instead, silent reading fluency tests consistently relied on some other measurable behavior within the assessment process to gage reading time, such as underlining the text as it is read, placing slashes between words, clicking a key to move from one segment of the text to another, or circling the last word read (see Price et al., 2012 for a more exhaustive review). Although these approaches to measuring silent reading are feasible to use in school contexts, data are mostly limited to reading rate, leaving uncertainty about more complex reading behaviors such as pauses and regressions, and suffer from an overall lack of precision (Price et al., 2012). Hiebert et al. (2010) has raised concern about the issue of students engaging in fake reading, which is especially common among struggling readers whose silent reading rate is assessed via self-report (Fuchs et al., 2001). Fortunately, technological advances in eye trackers now allow researchers to collect data as students read from a computer screen (Benfatto et al., 2016), making available a trove of rich and precise data about the reader's behavior. Adopting eye-tracking technology also diminishes the extra strain associated with traditional assessments, such as the need for verbal or written responses from readers, as well as the role of skills irrelevant to silent reading (e.g., fine motor skills needed for circling or underlining).

Eye-tracking

Eye-tracking measures have demonstrated the capacity to provide detailed records of behaviors and underlying processes readers engage in, as well as indications of specific skill development (Mason et al., 2013; Miller & O'Donnell, 2013; Rayner et al., 2013). Reading research has consistently indicated patterns of two broad eye movement (EM) categories: saccades (rapid movements) and fixations (pauses) (Foster et al., 2018). Saccades are characterized by suppressed vision as students move their eyes from one point to another, whereas fixations consist of extracting information from fixated points and the surrounding areas (Rayner et al., 2006). Relatedly, most movements consist of rightwards saccades or return sweeps as readers move from the end of one line to the start of the next, although readers sometimes make regressions, or backward saccades, to process previously read information (Foster et al., 2018; Just & Carpenter, 1980; Rayner et al., 2006).

Among current eye-tracking studies, the most common measures focus on temporal (time spent looking at a word), count/proportion (number of gazes and fixations, proportions of regressions and refixations), and spatial (how far the eyes move prior to landing on the word) skill areas (Kim et al., 2019). Previous analyses of varying ages and grade levels have yielded general reading performance improvements over time, as well as longer saccades, shorter and fewer fixations per word, and fewer refixations and regressions (McConkie et al., 1991; Valle et al., 2013). Researchers use many eye movement measures that capture various aspects of word-level fixation behavior and are thought to reflect specific skills related to textual processing (Foster et al., 2018). Specifically, it is understood that beginning stages of word processing are reflected by eye movement behaviors such as first-fixation duration (time spent on the initial fixation on a word independent of the number of fixations on that word), refixation duration, (time a reader spends refixating on a word after the first-fixation), and rereading duration (time spent returning to a word after reading the proceeding word or words) represent unique processes. Additional behaviors include number of gazes per word (the sum of all fixations on one word before moving to another word) and total fixation duration (total duration of all fixations, including regressions, on a word). Total fixation duration reflects higher-level or integrative processing stages due to the roles of fixations and rereading times during varying passes through a word. Beyond the word-level, researchers often assess eye movements in terms of wider target regions to understand processing at the sentence- or discourse-level (Rayner et al., 2006). Therefore, despite our knowledge about the utility of word-level data, many earlier studies of eye movements have assessed reading at the passage level (e.g., Ashby et al., 2013; Foster et al., 2013; Joseph et al., 2013; Vorstius et al., 2013).

To further understand these processes, multiple computational reading models have been introduced, combining skills of linguistic processing and oculomotor control (Kim et al., 2019). Overall, among adult readers whose eye movements are less constrained by decoding skills, empirical evidence points to three hypothesized higher-order indexes, including orthographic processing, lexical access, and integration factors (Kim et al., 2019, 2022). Notably, these empirically driven models share the basic assumption that certain eye movements are related to specific underlying cognitive processes (Engbert et al., 2002; Reichle et al., 2003; Reilly & Radach, 2006; Yang, 2006). It is assumed that initial decoding processes (e.g., orthographic processing) are captured by the duration of the first fixation. Lexical/semantic processing is relevant to refixation duration (Inhoff, 1984; Inhoff & Radach, 1998; Rayner & Pollatsek, 1987) while higher-order syntactic integration processes are characterized by rereading duration (Frazier & Rayner, 1982; Kim et al., 2019, 2022; Radach et al., 2008; Radach & Kennedy, 2004; Rayner et al., 2006).

Concerning psychometric properties of eye-tracking technology with children, many older studies demonstrate adequate reliability and validity (De Luca et al., 1999; McConkle et al., 1991; Tinker, 1936), although limited information exists regarding more contemporary eye-tracking measures. In a more recent study, Foster et al. (2018) explored the psychometric properties of multiple eye movement behaviors such as fixations, gaze durations, regressions, and proportion of words initially skipped in a sample of children ages seven to eight. Overall, findings indicated that measures of eye movements have the capacity to capture a notable degree of variability within multiple reading skill areas.

Generally, as readers develop, eye movements become characterized by fewer refixations and regressions, shorter and fewer fixations per word, and wider recognition spans, all of which point to developments in linguistic skills rather than oculomotor control changes (Huestegge et al., 2009; Hutzler & Wimmer, 2004). Findings yield that most young readers engage in contradictory processes compared to those of adults, as beginning readers assumingly do not possess the needed metacognitive abilities to carry out the behaviors common to adult readers, such as skilled skipping of words and intentional regressing to clarify meaning (Rayner et al., 1998; Valle et al., 2013). However, it should be noted that among children in fourth grade, this age range is often considered a transitional period of metacognition development (Chall, 1983). Readers of higher skills, although less efficiently, tend to demonstrate similar eye movement behaviors during reading as adults, with more and longer fixations per word, and generally more regressions (Blythe et al., 2011).

Oral and Silent Reading

Across the minority of eye-tracking studies with a focus on children in the past 10 years, few studies have considered both oral and silent reading modalities (e.g., Foster et al., 2018; Kim et al., 2019; Krieber et al., 2017; Vorstius et al., 2013) whereas most focus on only one reading mode (Ashby et al., 2013; Bayram et al., 2012; Benfatto et al., 2016; Blythe & Joseph, 2011; Sperlich et al., 2015, 2016; Valle et al., 2013). Overall, the literature consistently indicates that as readers develop skills, they read more quickly (Vorstius et al., 2014). Concerning both children and adult eye-tracking studies, there is consensus that it takes more time to read orally than silently, likely due to a greater devotion to processes such as intonation, pronunciation, and monitoring (Ashby et al., 2012; Vorstius et al., 2014). Across studies with adults, there is agreement that word frequency greatly interacts with reading skills and has greater effects among higher skilled readers (Ashby et al., 2005; Haenggi & Perfetti, 1994). Regarding studies with adults engaging in silent reading, there is consensus that shorter fixations are common when readers encounter shorter, familiar, or frequently occurring words (Clifton et al., 2007; Inhoff, 1984; Inhoff & Rayner, 1986; Reichle et al., 2003), all of which are skipped over more often (Brysbaert et al., 2005; White, 2007). Specifically, during silent reading, about 15% of all saccades are regressions, implying that one to two out of 10 saccades regress against the typical reading direction, and back to already read material (Rayner, 1998). Spatial measures also indicate that most saccades during silent reading comprise six to eight letters and that the initial landing position of the eyes is often halfway between the beginning and middle part of a word (McConkie et al., 1988, 1989; O'Regan, 1981; Radach & Kempe, 1993; Rayner et al., 1998).

When comparing average and highly skilled second-grade readers, Valle et al. (2013) found that average readers demonstrated more fixations and skipped about half of the words during silent reading. Strategic skipping observed in adults was not characteristic of highly skilled readers in this study, as the advanced second-grade participants skipped more than one-third of words read on first reading pass. It has been demonstrated that the greatest predictor of word skipping is length, as short words are consistently skipped more often (Brysbaert & Vitu, 1998; Rayner, 1979). For example, Vitu et al. (1995) revealed skipping probabilities of approximately 80% for one-letter words, 60% for three-letter words, 30% for five-letter words, and 10% for words that were seven letters or longer. There is also widespread agreement that word-frequency effects exist among children and adults, as children fixate longer on infrequent words (Inhoff & Rayner, 1986; Rayner & Duffy, 1986). Among adult readers, it is understood that probability of skipping depends on the types of words being read (Pynte & Kennedy, 2006), and much attention has been dedicated between content and function words. Content or lexical words consist of nouns, adjectives, verbs, and adverbs, whereas function words include all remaining categories including prepositions, articles, conjunctions, particles, and auxiliary verbs

(Nation, 2016). EM studies have consistently indicated that function words are fixated approximately 35% of the time whereas content word fixations fall at about 85% (Carpenter & Just, 1983; Rayner & Duffy, 1988), indicating greater ease associated with reading function words. Overall, evidence points to greater popularity of function words compared to content words in children's text (Stuart et al., 2003).

In addition to effects from word features, eye-tracking studies also demonstrate that reading modality often predicts eye movement behaviors among children. Kim et al. (2019) found that first-grade readers exhibited longer duration and a higher number of fixations and gazes during oral reading when compared to silent reading at the beginning and the end of the school year. Specifically, children spent more time looking at words before moving onto the next word (e.g., longer refixation durations) and in the total time allocated to looking at the word (e.g., rereading time, or revisiting the word after leaving it) during oral rather than silent reading. In a longitudinal study examining the trajectories of eye movements from grades one to three, students demonstrated shorter initial fixation durations and fewer fixation and gaze counts during oral and silent reading as they developed (Kim et al., 2022). However, reading modality predicted differences in other eye movements, as students exhibited longer and more frequent fixations when engaging in oral reading, likely due to extra processes required in oral reading. Next, when comparing average and advanced readers in the second grade, Valle et al. (2013) found that shorter total reading times and gaze durations, and fewer regressions between target and previously read text were characteristic of above-average silent readers. Highly skilled readers also engaged in strategic pausing when they encountered low-frequency words. Further, in the only large-scale study to examine eye movements and word-frequency effects during both oral and silent reading modes, Vorstius and colleagues (2014) employed a cross-sectional study involving students through first and fifth grade. Oral reading was characterized by fewer interword regressions and more prolonged and frequent fixations compared to when children read silently, suggesting that as with traditional reading measures, the eye-voice coordination associated with reading aloud may create constraints for students (Vorstius et al., 2014). Word-frequency effects were also dependent upon reading mode, as early readers exhibited a higher number of regressions to low-frequency words during silent rather than oral reading. Notably, weaker comprehenders showed slower reading rates and smaller word-frequency effects, likely due to a smaller mental lexicon and slower decoding of high-frequency words associated with infrequent exposure to text.

Beyond oral and silent reading behaviors, eye movement studies have also contributed to knowledge related to reading comprehension (Rayner et al., 2006; Vorstius et al., 2013). After examining the effects of comprehension skills on reading rate at the sentence-level, Vorstius et al. (2014) indicated that slower child readers also demonstrated weaker comprehension skills, and this was more pronounced during oral versus silent reading. When reading silently, strong comprehenders spent more time on difficult words that were lower in frequency, causing a larger increase in total viewing time spent on low-frequency words when reading silently for stronger comprehenders. However, this frequency effect was reduced when reading aloud, and reading mode differences were almost identical on high-frequency words for strong and weak comprehenders alike. These findings highlight that among readers with less developed comprehension skills, the articulation of unfamiliar words when reading aloud may be more impactful compared to strong comprehenders. In sum, very few reading comprehension studies exist using eye-tracking technology, and more studies are needed to explore the effects of reading modality on comprehension skills through the lens of eye-tracking.

As previously discussed, limited research has employed SEM analyses to examine oral and silent reading fluency with reading comprehension (Kim et al., 2011; Price et al., 2016; Turkyılmaz et al., 2014; Robinson & Meisinger, 2021), and only one eye-tracking study to date has considered these reading skills using SEM analytic techniques (Kim et al., 2019). Specifically, Kim and colleagues (2019) examined changes in oral and silent reading across the school year among a normative sample of 368 first graders, with an overall focus on relations with reading proficiency. Participants were administered three oral and three silent passages in the fall and the spring, and researchers collected eye movement behavior data including first-fixation duration, initial landing position, refixation duration, number of fixations in gaze, proportion of refixations, reading time, and number of gazes per word. Factor analysis was first employed to determine the factor structure of the eye movement measures, and three alternative confirmatory factor models were tested. Model one was designed to be consistent with adult literature (e.g., Engbert et al., 2002; Reichle et al., 2003; Yang, 2006) and was comprised of a three-factor model, including the early orthographic processing, lexical/semantic processing, and higher-order integration factors (Kliegl & Laubrock, 2017). Model two consisted of a single-factor comprised of all eye movement indices whereas model three was a second-order factor model. Specifically, index-level factors were included along with factors of orthographic processing, lexical/semantic processing, and higher-order integration factors. However, each of the three models yielded poor model fit, leading the authors to conduct an exploratory factor analysis (EFA), which yielded a 10-factor model including index-specific factors, passage-specific factors, and a global factor. A bifactor model was then specified to test for passage-specific factors, index-specific factors, and a general factor of eye movements.

Overall findings from Kim et al. (2019) revealed that readers looked at words for a longer time and with more gazes and fixations when reading orally compared to silently, which is consistent with the literature supporting that oral reading requires additional cognitive resources (Ashby et al., 2012; Vorstius et al., 2014). Next, in contrast with studies involving older students who exhibit associations between silent reading and comprehension skills, oral reading and passage comprehension among first graders were strongly correlated whereas silent reading exhibited a weak correlation with comprehension of passages. Specifically, students with high reading proficiency skills demonstrated stronger relations between eye movements with word reading and reading comprehension. It was also found that first graders demonstrated more oral versus silent reading differences in the fall when compared to spring EMs, perhaps reflecting the challenges related to decoding and phonemic processing common during the acquisition of early reading skills. As such, eye movements during oral reading were characterized by more time spent rereading and refixating on words and more frequent fixations (i.e., looking at words) during the fall when compared to spring. In addition, eye movements were associated with word reading and comprehension among highly skilled readers in the beginning of the year, whereas struggling readers' eye movements were minimally associated with reading skills. However, these findings stabilized by the spring, indicating that among beginning readers, skill development changes rapidly.

Kim et al. (2019) proposed that the general eye movement factor revealed in their study may be attributed to beginning readers' highly constrained skills related to decoding, which serves as a bottleneck when students are in the beginning stage of word reading. Therefore, it seems reasonable that the hypothesized higher-order indexes (e.g., orthographic processing, lexical/semantic processing, and higher-order integration factors), which did not fit the data with beginning readers, may be characteristic of more skilled child and adult readers whose eye movements are less constrained by decoding skills. Considering that the factor structure of eye movements among child readers remains unclear, additional research using such analytic approaches is needed, specifically those that consider the relations of oral and silent reading and reading comprehension.

Purpose

The current study is an attempt to further our knowledge about online reading processes as measured by eye movements during oral and silent reading, and their relations to reading comprehension. This study focused on students in fourth and fifth grade, as it is widely assumed that by late elementary school, children demonstrate sufficient oral reading skills and are able to transition to silent reading (Chall, 1983, 1996). Eye-tracking provides information beyond that of traditional reading measures, and comparisons between eye movement characteristics during oral versus silent reading help bridge the gap between the eye-tracking and reading modality literatures. Notably, this study was also the first to examine reading modality and eye movement behaviors at the word-level among fourth and fifth graders using SEM analytic techniques, as only one study has explored the factor structure of eye movement behaviors during oral versus silent reading (Kim et al., 2019). Comparing oral and silent reading fluency skills and eye movement behaviors between fourth and fifth graders expanded our understanding of not only developmental differences during this period, but also how reading modality affects comprehension skills. To this end, cross-sectional data from a normative sample of students in grades four and five within a school district in California were examined. Grade-level benchmark passages and eye-tracking technology were utilized to assess students' oral and silent reading fluency skills, and students' eye movements were tracked as they read one oral and one silent grade-level passage on a computer (Benfatto & Seimyr, 2016). An adaptive, computer-based measure of reading comprehension was also administered. Specific research questions are as follows:

1. What are the characteristics of eye movement behaviors in oral and silent reading for children in grades four and five, and do they differ between grades?
2. Do eye movement behaviors during oral and silent reading present an underlying factor structure?
3. How are eye movement behaviors related to oral and silent reading fluency and comprehension among students in fourth and fifth grade?

To approach the first research question, an analysis of variance (ANOVA) was conducted to determine eye movement differences between reading modality and grade level. Specifically, this approach allowed for descriptions of eye movement behaviors during oral versus silent reading, and whether these characteristics differ between students in the fourth and fifth grade. Given the overlap between this analysis with analytic methods adopted by prior studies, this approach also created a bridge with prior eye-tracking literature (e.g., Kim et al., 2019; Valle et al., 2013). Based on the previous work related to reading modality and eye movement behaviors across developmental levels, it was assumed that students in fifth grade would demonstrate more evidence of strategic reading overall compared to fourth graders, as they have developed more advanced decoding skills (Chall, 1983, 1996). Strategic reading among fifth graders can also be considered a result of metacognitive skills, as they are expected to be further along in the transitional phase of metacognition compared to fourth graders who are just beginning this period (Chall, 1983). Furthermore, it was expected that fifth graders would exhibit fewer and shorter single- and first- fixations per word, as well as fewer refixations and regressions (e.g., leftward saccades) (McConkie et al., 1991; Valle et al., 2013). It was thought that they would also commit more interword regressions (i.e., refixating text to the left of the current word), as interword regressions are related to availability of cognitive resources (McConkie et al., 1991). Regarding modality-specific hypotheses, it was expected that readers would exhibit significant eye movement differences during oral and silent reading, as oral reading is associated with more frequent and longer fixations (Ashby et al., 2012; Vorstius et al., 2014). Students would also exhibit fewer interword regressions during oral reading due to greater reliance on cognitive resources (McConkie et al., 1991). Finally, although this study anticipated that students in fourth and fifth grade are undergoing the transition from fluent oral to silent reading, it is assumed that those in fifth grade would exhibit more salient benefits of silent reading, whereas oral reading would be a hinderance (Rayner, 1998).

To explore the second research question, which aims to determine if an underlying factor structure of eye movement behaviors exists during oral and silent reading, the three-factor model employed in Kim et al. (2019) (e.g., orthographic processing, lexical/semantic processing, and higher-order integration factors) were replicated as latent variables in this study. Eye movements during oral and silent reading were modeled separately for each grade by employing four confirmatory factor analyses (CFAs) (see Figure 1). Although this three-factor model did not fit the data in the study with first graders by Kim et al. (2019), this work adopted this model with more advanced readers who assumedly would exhibit more advanced metacognitive and reading abilities. It is likely that the three-factor model consists of skills that are more similar to those of adult readers, as it is assumed that fourth and fifth graders are beginning to show more advanced reading abilities (Blythe et al., 2011; Chall, 1983). Consistent with the approach of Kim et al.

(2019), the orthographic processing latent variable was comprised of single- and first-fixation duration, and total fixation time. The indicators associated with lexical/semantic processing included refixation duration, fixations per word, and refixation probability at the word level. The higher-order syntactic integration processing factor consisted of rereading duration, number of gazes per word, and probability of making interword regressions. A latent reading comprehension variable was comprised of measures from i-Ready Diagnostic (Curriculum Associates, 2018), including vocabulary skills and comprehension of literature and informational text (see Figure 1).

Figure 1. Measurement Models for the Eye Movement and Reading Comprehension Factors

To address the third question concerning how eye movement behaviors are related to oral and silent reading fluency and reading comprehension based on grade level, structural equation modeling was used once the measurement models were confirmed. Oral and silent reading was modeled separately for each grade, and reading fluency was represented as observed variables to examine effects on reading comprehension (see Figure 2a and 2b). In the oral reading model, reading fluency was represented by the number of words read correctly per minute metric (WCPM) whereas reading rate was measured by words per minute (WPM) which served as an indicator for reading fluency in the silent reading model. Considering the underlying factor structure of eye movement measures in developing readers is unknown, the overall analysis of their relation to reading fluency and comprehension is exploratory in nature. Given the capacity suggested by the literature for eye movement behaviors to yield information about the underlying processes involved in reading, it seems reasonable to hypothesize that these variables would make a significant contribution to both reading fluency and comprehension. Finally, based on prior studies with late-elementary school students (e.g., Dickens & Meisinger, 2017; Price et al., 2015; Prior et al., 2011; Robinson et al., 2018), it was expected that reading fluency would make significant contributions to reading comprehension across both modalities and grade levels.

Figure 2. Multigroup SEM by Modality

Figure 2a.

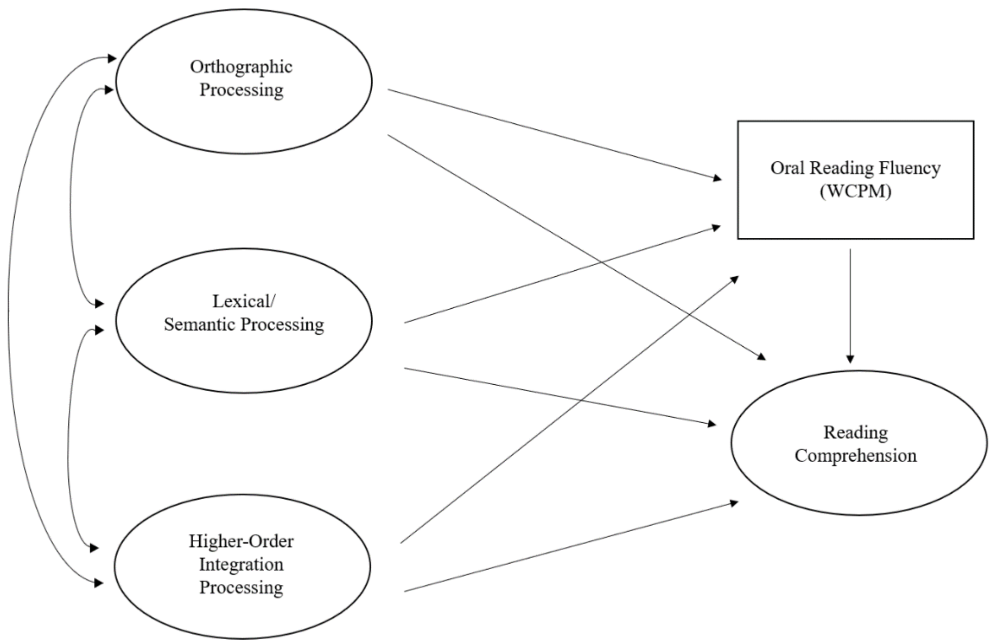
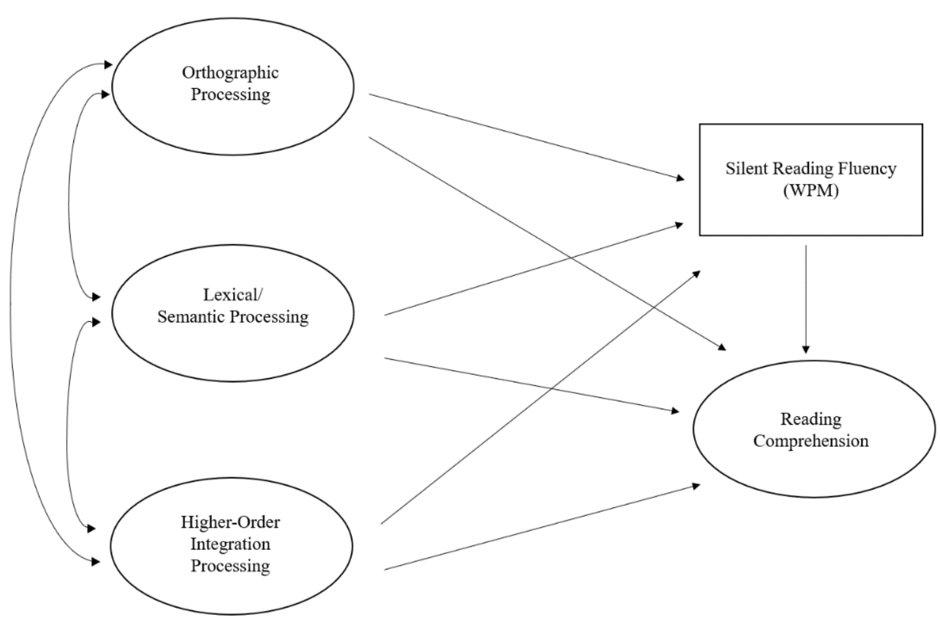


Figure 2b.



Method

Participants

Participants in this study were drawn from a larger study examining computer-based benchmark reading measures. Data were collected by the participating public school district in the fall, winter, and spring of one academic year. In this study, only data available from the fall benchmark were considered. The following inclusion criteria were used to select participants for this study: (a) attendance in grades four and five, (b) Lexplore and i-Ready data available within the fall timepoint (August to November), (c) data were collected no more than 12 weeks apart, (d) and students were not classified as English language learners. These criteria resulted in an available sample of approximately 545 students in grades four (n = 310) and five (n = 235) attending four elementary schools in a public school district located in California. Of those students, 84 had an active individual education plan (IEP). Per school district guidelines, all students participated in the benchmark assessments except for those presenting the most significant disabilities whose IEP indicated the use of alternate measures. According to the school records, participants' racial group membership was approximately 6% American Indian/Alaska Native, 10% Black/African American, 8% Other students, and 76% White. In terms of ethnicity, approximately 36% of students identified as Hispanic/Latinx, and approximately 50% were male. Free and reduced lunch (FRL) status was used as a proxy for socioeconomic status, with approximately 50% of students qualifying for FRL.

Measures

All tests were administered by school personnel as part of their routine benchmark screening procedures. De-identified student data, including the i-Ready Diagnostic and demographic information (grade level, gender, race and/or ethnic identity, English language learner status, existing IEP, and FRL status) were made available by the school district. Data related to the Lexplore benchmark passages, including eye movement data, reading times, and reading errors, were provided by the test publisher.

Apparatus

To examine students' eye movement behaviors during oral and silent reading, this study utilized Lexplore (Lexplore AB, www.lexplore.com), a new tool that employs eye-tracking technology and machine learning models to screen for reading difficulties (Meisinger et al., 2022). Lexplore was administered by school professionals (primarily teachers) using a laptop computer and an additional external monitor (15.6-inch screen with full HD 1920x1080 resolution and with 100% display scale settings). The remote near-infrared Tobii 4C eye-tracker (Tobii Technology AB, www.tobii.com) was used to record eye movements. The device is mounted below the display with an operating distance of 50 to 95 cm and provides a track box of 40 x 30 at 75 cm. The 4C is a consumer product aimed for gaze interaction and is licensed to Lexplore for analytic purposes to assess reading.

To prepare for the assessment, participants were positioned in front of the display at a distance of 65 centimeters. To ensure adequacy of the setup, a visualization was presented to the teacher for reference. Next, the system was calibrated using a five-point calibration pattern. The eye tracker provided binocular data at a sampling rate of 90 Hz. Under optimal conditions the precision is 0.1 degrees (Root Mean Square) with an accuracy of 0.3 degrees.

Eye Movements

The eye movement variables employed within this study were at the word-level, indicating that behaviors demonstrated within individual words were not considered. Variables selected for this work are consistent with word-level measures utilized across prior eye-tracking studies (e.g., Foster et al., 2018; Kim et al., 2019; Krieger et al., 2013; Sperlich et al., 2015; Yan et al., 2013), and are related to the categories of reading duration, fixations, and regressions. Specifically, individual EM variables include single- and first-fixation duration, gaze duration, and total fixation time. Refixation duration, fixations per word, refixation probability, rereading duration, number of gazes per word, and probability of making interword regressions were also used. A description of each eye movement variable is provided in Table 1. Notably, long data were used to develop the machine learning models utilized by Lexplore (Seimyr, 2021) and the provided scores have been supported for use among students in the United States (Meisinger et al., 2022). However, rather than using the norm-referenced scores provided by machine learning modeling, raw eye movement data were utilized in the current study.

Table 1.

Eye-Tracking Variable Descriptions

Variable	Description
Single-Fixation Duration	Duration of the fixation/pause when only one total fixation is made on a word
First-Fixation Duration	Duration of the first fixation/pause on a word regardless of the number of fixations made on a word
Total Fixation Duration	Summed duration of all fixations/pauses and regressions on a word
Refixation Duration	Amount of time spent refixating on a word immediately after the initial fixation
Number of Fixations Per Word	The number amount of fixations/pauses on a word
Refixation Probability	Percentage of spent refixating on a word out of the total time spent fixating on the same word
Rereading Duration	Time spent reading a word after the initial gaze
Number of Gazes Per Word	The number of fixations/pauses on a word before moving on to the next word
Interword Regression Probability	Percentage of time spent rereading a word out of the total time spent fixating to the left of the target word

Regarding the psychometric properties of EM measures, Foster and colleagues (2018) found adequate support for test-retest and alternate-form reliability for first-fixation duration, gaze duration, regressions, and fixations, with coefficients falling above .70. Specific EM measures also demonstrated criterion-related validity, as students' scores in basic reading, broad reading achievement, reading fluency, word attack, and passage comprehension were moderately to highly correlated with fixation durations. However, weaker correlations existed with regressions or count/frequency of fixations (Foster et al., 2018). Eye movement measures also seemed to be weakly correlated with more specific reading skills, including morphological awareness and nonsense word identification (Foster et al., 2018).

Reading Passages

After completing a short eye calibration exercise, participants in both grades were asked to read two grade-level narrative passages. The first passage was read aloud and the second was read silently. Notably, given that the texts used in this study were benchmark passages, they were not constructed to control for word frequency or ratio of word length or type (i.e., content versus function words). According to the test publisher, the following criteria were applied when designing the texts: (a) passage subjects are similar to other grade-level text, (b) text are equal in complexity within grade levels, (c) equal geometric properties when presented on the screen (e.g., equal line length and number of lines), (d) passages should be readable to most students in the grades, and (d) the passages should contain connected narrative to allow reading for comprehension. Notably, compared to texts employed among fourth graders, the fifth-grade texts were designed to include more details and were longer overall. The fourth-grade oral passage consisted of 62 words and nine sentences, and the silent passage included 57 words and 10 sentences. The fifth-grade oral passage contained 72 words and five sentences whereas the silent passage consisted of 68 words and six sentences.

Descriptive statistics for the passage word characteristics are provided in Table 2. Consistent with common texts designed for children, the passages consisted mostly of function words (e.g., articles, conjunctions, particles, auxiliary verbs) rather than content words (e.g., adjectives, nouns, verbs, adverbs) (Stuart et al., 2003). Content words comprised about 50% of the oral and silent passages for fourth graders. Approximately 39% of the oral fifth-grade passage included content words whereas 38% of the silent passage consisted of content words. Individual words within the four passages were also coded for frequency using the TASA index (Touchstone Applied Science Associates: Zeno et al., 1995) band levels developed by Zeno et al. (1995). Regarding the fourth-grade passages, 51% of the oral text and 49% of the silent passage included high-frequency words (TASA > 70). For fifth-grade passages, 46% of the oral text were high-frequency words whereas 57% of the silent passage consisted of high-frequency words. Notably, across all four passages, low-frequency words (TASA < 50) comprised less than one percent of each text (i.e., four or five words per passage). All other words fell between TASA values of 50 and 70 and were not coded as low- or high-frequency. In accordance with common standards utilized by prior literature regarding word length (e.g., Blanchard et al., 1989; Rayner, 1998; Vitu et al., 1995), words of three letters or less were considered short whereas long words included between six and 10 letters, and words between four and six letters were not coded. Furthermore, short words comprised between 44% to 47% of all four passages whereas long words constituted 30% or less.

Table 2.

Passage Word Characteristics

	Grade 4		Grade 5	
Characteristic	Oral Passage	Silent Passage	Oral Passage	Silent Passage
Word Type				
Content	31	30	28	26
Function	31	27	44	42
Word Frequency				
Low	4	4	5	4
High	32	28	33	39
Word Length				
Short	27	26	31	32
Long	4	17	17	21

Note. Grade 4 Oral Passage consisted of 62 words; Grade 4 Silent Passage consisted of 57 words; Grade 5 Oral Passage consisted of 72 words; Grade 5 Silent Passage consisted of 68 words. Word frequencies were determined by the TASA Index (Zeno et al., 1995), with TASA < 50 for low-frequency words and TASA > 70 for high-frequency words. Short words were comprised of three letters or less. Long words consisted of six to 10 letters.

Reading Fluency

Participants' oral and silent reading fluency were also assessed by the Lexplore software. As students read the first passage aloud and the second silently, the time spent reading each passage was recorded automatically by the software, along with children's oral reading of the first passage. Each passage reading was followed by the completion of three explicit comprehension questions to encourage reading for understanding, which were not used to measure skill. Graduate students in school psychology with prior training in reading assessment reviewed audio recordings of the oral passage to determine the number of errors, with a reported inner-rater reliability ($r = .99$) was based on 30% of passages (Meisinger et al., 2022). Reading errors included substitutions, omissions, hesitations of more than three seconds, reversals, and words provided by assessor. Insertions, repetitions, self-corrections within three seconds, and dialectical differences were not considered errors. Although Lexplore yields z-scores and percentile ranks for oral and silent reading as well as a combined score, this study considered words correct per minute (WCPM) metric as the main indicator of oral reading fluency to be consistent with the broader literature. The reading time (in seconds) and the number of words read correctly (number of words in passages – number of reading errors) were used by the software to calculate the WCPM using the following formula (number of words correct/reading time in seconds) X 60 = WCPM). For passages read silently, the words per minute (WPM) was calculated (number of words in passage/reading time in seconds) X 60 = WPM). Data from the technical manual reported an overall test-retest reliability of .85 for grades one through eight for passages administered one week apart. Additionally, a strong concurrent relation was found between Lexplore and i-Ready (r = .75) (Meisinger et al., 2022). When fall Lexplore data for grades three to eight were used to identify those at-risk for not passing an end-of-year state test (i.e., the California Assessment of Student Performance and Progress), an overall AUC of .81 was found for z-scores and an AUC of .82 for the WCPM metric used in this study (Meisinger et al., 2022).

Reading Comprehension

i-Ready Diagnostic (Curriculum Associates, 2018) is an adaptive, computerized measure of reading that is commonly used for progress monitoring and benchmark screening within classroom settings (Curriculum Associates, 2018). Students in grades four and five are first administered 18 items in the Vocabulary domain, followed by 18 items in the Reading Comprehension: Literature domain, and 18 items in the Reading Comprehension: Informational Text domain. Upon completion of these subtests, the test flow is adjusted based on the overall estimated ability score. If a student falls below grade-level expectations on these three domains, basic reading domains (i.e., Phonics, High-Frequency words) are administered, and these additional domains contribute to the overall Reading Domain score as needed. To ensure only the three core domains are included across all participants, only the domain scores were used as indicators of reading comprehension in this study. Within the Vocabulary domain, students are required to read a sample sentence containing one target word and then choose the meaning of the target word among a list of options. The Reading Comprehension domains require students to click and move sentences into a response box or click within the passage to respond to presented questions about the passage. The number of correct responses provided by the student then determines the total number of Reading Comprehension items presented to complete. Therefore, the two domains are formed by the ratio of correct to incorrect responses.

i-Ready yields scaled scores for each domain ranging from 100 to 800 and an overall score following interactive item response theory modeling. Per the test manual, across grades two through six, the overall score yielded test-retest reliabilities between .85 to .86 following a 12-to-18-week time interval (Curriculum Associates, 2018). Marginal reliability fell between .96 and .97 and the mean standard error of measurement for the overall score fell between 10.0 and 10.5. Across the Vocabulary, Reading Comprehension: Literature, and Reading Comprehension: Informational Text domains, marginal reliability ranged from .88 to .91 at grades four and five (Curriculum Associates, 2018). When comparing the Reading Domain overall score to the Lexile Linking Test for grades one, three, five, and seven, concurrent validity fell between .88 and .89 across the four grade levels. When comparing the i-Ready Diagnostic for grades three through eight to statewide tests administered at the end of the year (i.e., the Florida Standards Assessments test, the Smarter Balanced Assessment Consortium test, the New York State

Testing Program test, and the Partnership for Assessment of Readiness for College and Careers test), the median correlations were between .77 to .81 in the fall, .77 to .83 in the winter, and .78 to .84 in the spring.

Procedure

All data were collected by school personnel (primarily classroom teachers) during the 2018-2019 school year as part of the school's routine assessment battery. Fall data were collected between September and November by the district, and students' assessment dates for Lexplore and i-Ready fell within two months of one another. Lexplore measures were administered individually within a classroom or another quiet location in the school and required about five minutes to administer. i-Ready Diagnostic reading measures were administered in a group setting, and often required over an hour due to inclusion of reading and math subtests. The UM Institutional Review Board (IRB #PRO-FY2022-448) determined that this study did not involve human subjects as it consisted of secondary analysis of existing de-identified data, and therefore did not require approval.

Analytic Approach

To address the first research question related to characteristics of eye movements in oral versus silent reading and if they differ based on grade, an analysis of variance (ANOVA) was conducted using IBM SPSS Statistics (Version 28). The dependent variables were 18 oral and silent eye-tracking measures. The nine dependent eye movement variables included oral and silent single-fixation duration, first-fixation duration, total fixation duration, refixation duration, number of fixations per word, refixation probability, rereading duration, number of gazes per word, and interword regression probability. Effect sizes in the form of η2 were also reported, with .01 indicating a small effect size, .06 indicating medium, and .14 indicating large. Finally, family-wise error was controlled for using Bonferroni correction (.05/9) with $p < .01$.

To address the second research question aiming to determine if eye movements during oral and silent reading comprise an underlying factor structure, four CFAs were to be conducted using MPlus v8.6 (Muthén & Muthén, 2017) to represent grade and modality (see Figure 2). Consistent with procedures utilized in Kim et al. (2019), if the CFAs failed to support the proposed measurement model, exploratory factor analysis (EFA) would be conducted to examine eye movement factor structures for both grades. For the CFAs, maximum likelihood estimation with robust standard errors (MLR) was used to account for any multivariate outliers and to handle missing data. Standardized values were interpreted, although the unstandardized coefficients were examined to determine statistical significance. To analyze the factor loadings of the indicators, an asymptotic factor covariance matrix of the polychoric correlations and error covariance matrix was interpreted with reported standardized coefficient estimates.

As suggested by Kline (2023), model fit was evaluated using multiple indices including the chi-square and degrees of freedom, Bentler comparative fit index (CFI; Bentler, 1990), Steiger-Lind root mean square error of approximation (RMSEA; Steiger, 1990) with its 90% confidence interval, and the standardized root-mean-square residual (SRMR). Two goodness-of-fit measures, the Akaike Information Criteria (AIC; Akaike, 1998), and the Bayesian Information Criterion (BIC; Schwarz, 1978), were also used to compare fit between non-nested models. A significant chi-square value implies poor model fit, as it evaluates the null hypothesis. For the CFI, values greater than .95 suggest good model fit and are compared to a model in which all included variables are assumed to correlate. Concerning the RMSEA using a 90% confidence interval, a model would be considered an insufficient fit to the sample if the lower bound of the confidence interval is less than or equal to .05, whereas the null hypothesis of poor fit would be rejected if the upper bound of the confidence interval is .10 or greater (Steiger & Fouladi, 1997). Regarding SRMR, values less than .10 indicated good model fit (Hu & Bentler, 1999). Factor loadings of .70 or higher were considered good fit (Kline, 2016).

Once the measurement model has been validated, oral and silent reading fluency was integrated into the models separately as observed variables to address the third research question (see Figures 3a & 3b). WCPM served as the indicator for oral reading fluency whereas silent reading fluency was comprised of reading rate, and reading fluency predicted reading comprehension in both models. It was expected that both latent eye movement factors would have direct paths to reading fluency and reading comprehension. Within both models, standardized and unstandardized regression coefficients were utilized to determine the indirect and direct relations among the variables (i.e., oral and silent reading fluency, reading comprehension). Per Kline's recommendations (2016), standardized coefficient effect sizes greater than .05 were considered small, values above .15 were considered moderate, and those beyond .25 were interpreted as large.

Figure 3. Multigroup SEM by Modality

Figure 3a.

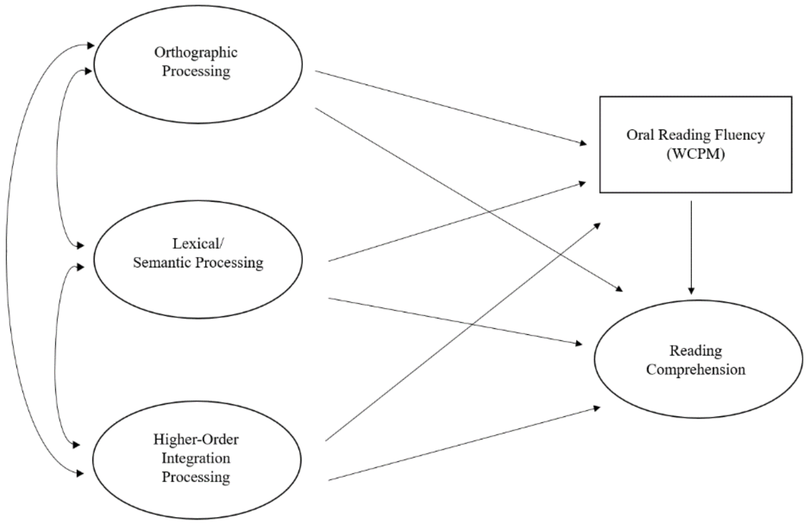
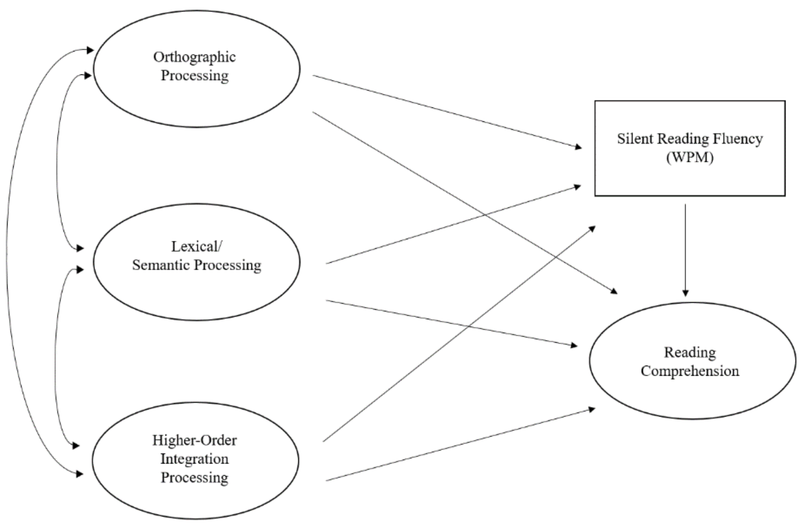


Figure 3b.



Results

Data Processing and Screening

Data were checked for any missing values, linearity, normality (i.e., skewness and kurtosis), and univariate and multivariate outliers (Tabachnick & Fidell, 2019). Independent-samples t-tests were used to check for differences across the two grade levels in demographic variables (gender, racial or ethnic group membership, and FRL status). Data were then screened for suitability for factor analysis.

Five participants were missing all or nearly all eye movement data due to technical difficulties or administration errors and were therefore dropped from the study. Three additional participants were also removed due to technical errors experienced during the recording which would have compromised the validity of the eye-tacking variables. Upon review of the WCPM variables, nine values were missing within oral WCPM, and two were missing silent WPM data. Based on examination of univariate outliers in the data ($|z| > 3.29$), 17 participants presented multiple and/or large outliers across the eye-tracking variables and were therefore removed from the dataset due to the large number of univariate outliers they accounted for in the data. The remaining 63 univariate outliers were addressed by replacing the scores with the nearest non-outlier score. Additionally, 30 multivariate outliers were identified (Mahalanobis distance chi-square value *p*s > .001) and were removed from the data, yielding a final sample size of 490 participants (277 fourth graders, 213 fifth graders). A frequency analysis indicated there were minimal missing values among the data (approximately 1%).

To ensure normality in the data, values of skewness and kurtosis were inspected for all WCPM, eye movement, and i-Ready variables. No skewness or kurtosis values among these data were greater than an absolute value of 2.0, indicating evidence of normality in the data. Pairwise plots were visually inspected for nonlinearity and heteroscedasticity and appeared to be within normal limits. Correlations among the indicators (> .80), the variance inflation factor (VIF, > 5.0), and tolerance values (< .10) were examined (Kline, 2016). First-fixation duration and total fixation duration consistently yielded extremely high correlations with several other eye movement variables across grade and modality (see Tables 3 and 4). These variables were dropped to avoid problems with multicollinearity for the measurement models that follow, but all variables were retained for the ANOVAs. Therefore, 12 indicators and 4 factors were examined in the CFA measurement model. The available sample size (N = 490) was determined to be adequate for the analyses (e.g., 12 indicators * 4 = 48; Tabachnick & Fidell, 2019). Prior to conducting SEM analyses, all variables were multiplied or divided by either 10 or 100 to maintain the recommended 1:10 ratio for variance (Kline, 2016). Independent-samples t-tests were used to check for differences in gender based on grade level and none were found, $t(488) = -.297$, $p = .708$. ANOVA was used to check for differences in race/ethnicity, $F(1, 489) = .125$, $p = .724$, $\eta 2 = .000$, and free/reduced lunch status, $F(1, 489) = 2.700$, $p = .101$, $\eta 2 = .006$, and no significant differences were found.

Table 3

Correlations between Variables in Oral Reading Model (N = 490)

Indicator	1	2	3	4	5	6	7	8	9	10	11	12	13
1. i-Ready Vocabulary	--	.73***	.75***	-.38***	-.36***	-.37***	-.28***	-.46***	-.18*	-.31***	-.40***	-.32***	..57***
2. i-Ready Literature	.74***	--	.79***	-.49***	-.45***	-.45***	-.32***	-.47***	-.18*	-.37***	-.36***	-.34***	.59***
3. i-Ready Information al Text	.72***	.81***	--	-.47***	-.44***	-.44***	-.32***	-.45***	-.14*	-.35***	-.37***	-.33***	.58***
4. Single-Fixation Duration	-.45***	-.42***	-.40***	--	.93***	.88***	.52***	.32***	.05	.64***	.34***	.13	-.62***
5. First-Fixation Duration	-.44***	-.40***	-.39***	.91***	--	.94***	.54***	.22**	.05	.69***	.28***	.04	-.57***
6. Total Fixation Duration	-.45***	-.40***	-.38***	.87***	.95***	--	.68***	.24***	.04	.87***	.30***	.06	-.62***
7. Refixation Duration	-.27***	-.28***	-.27***	.46***	.50***	.58***	--	.25***	.13	.55***	.29***	.07	-.44***
8. Fixations Per Word	-.48***	-.52***	-.52***	.41***	.28***	.26***	.23***	--	.08	.21**	.69***	.77***	-.77***

9. Refixation Probability	-.13*	-.15*	-.15*	.16**	.18**	.13*	.19**	.20***	--	.07	.54***	-.32***	-.17*
10. Rereading Duration	-.38***	-.37***	.33***	.67***	.72***	.86***	.43***	.26***	.12*	--	.26***	.04	-.55***
11. Gazes Per Word	-.44***	-.47***	-.44***	.44***	.39***	.37***	.30***	.73***	.58***	.33***	--	.09	-.60***
12. Interword Regression	-.27***	-.34***	-.35***	-.18**	.04	.02	.04	.78***	-.20***	.07	.18**	--	-.60***
13. Words Correct Per Minute	.58***	.59***	.58***	-.68***	-.65***	-.64***	-.42***	-.83***	-.29***	-.56***	-.74***	-.56***	---

*Note. ***p < .001;** p < .01; * p < .05* Bottom left = Fourth Grade; Top Right = Fifth Grade.

Table 4

Correlations between Variables in Silent Reading Model (N = 490)

Indicator	1	2	3	4	5	6	7	8	9	10	11	12	13
1. i-Ready Vocabulary	--	.73***	.75***	-.47***	-.46***	-.45***	-.28***	-.41***	-.18*	-.29***	-.43***	-.19**	.52***
2. i-Ready Literature	.74***	--	.79***	-.55***	-.54***	-.54***	-.36***	-.40***	-.23**	-.38***	-.42***	-.20**	.57***
3. i-Ready Informational Text	.72***	.81***	--	-.51***	-.51***	-.52***	-.35***	-.41***	-.17*	-.37***	-.41***	-.20**	.54***
4. Single-Fixation Duration	-.54***	-.50***	-.48***	--	.95***	.91***	.58***	.39***	.35***	.60***	.62***	-.00	-.73***
5. First-Fixation Duration	-.53***	-.50***	-.48***	.95***	--	.95***	.59***	.36***	.29***	.62***	.60***	-.01	-.73***
6. Total Fixation Duration	-.53***	-.50***	-.49***	.90***	.95***	--	.66***	.34***	.28***	.80***	.56***	-.03	-.73***
7. Refixation Duration	-.36***	-.32***	-.34***	.51***	.55***	.63***	--	.31***	.23***	.39***	.39***	.10	-.54***
8. Fixations Per Word	-.41***	-.41***	-.38***	.46***	.42***	.39***	.32***	--	.08	.19**	.69***	.74***	-.83***

9. Refixation Probability	-.31***	-.32***	-.32***	.25***	.23***	.23***	.22***	.31***	--	.27***	.51***	-.33***	-.27***
10. Rereading Duration	-.42***	-.39***	-.41***	.64***	.68***	.84***	.45***	.30***	.27***	--	.40***	-.10	-.51***
11. Gazes Per Word	-.47***	-.49***	-.43***	.51***	.51***	.50***	.36***	.79***	.64***	.44***	--	.06	-.76***
12. Interword Regression	-.10	-.08	-.10	.16*	.10	.08	.10	.70***	-.22***	-.02	.13*	--	-.50***
13. Words Correct Per Minute	.54***	.53***	.50***	-.75***	-.75***	-.76***	-.49***	-.85***	-.34***	-.61***	-.78***	-.50***	--

*Note. ***p < .001 ;** p < .01; * p < .05* Bottom left = Fourth Grade; Top Right = Fifth Grade.

Analysis of Variance (ANOVA)

To compare the characteristics of eye movement behaviors in oral and silent reading between grades four and five, a series of 2 (grade) X 2 (reading modality) mixed between-within subjects ANOVAs were conducted. Grade level (i.e., fourth and fifth) represented the between-subjects independent variable and reading modality (i.e., oral and silent) served as the within-subjects independent variable across all nine analyses. Levene's test of equality of error variances was used to confirm homogeneity of variance. Given that this approach tends to be overly sensitive with larger samples, Hartley's *F*max test (David et al., 1954) was used when Levene's test was significant (i.e., single-fixation duration, first-fixation duration, total fixation duration, rereading duration, and interword regression probability), and *F*max ratios were examined to confirm that values were close to one, indicating that the assumption of homogeneity of variance had not been violated (Hartley, 1950). Descriptive statistics for the eye-tracking variables are presented in Table 5. Statistics for interaction effects and main effects for all nine ANOVAs are reported in Table 6.

Table 5

Descriptive Statistics for Eye-Tracking Variables (N = 490)

	Grade 4 (*n* = 277)				Grade 5 (*n* = 213)			
	Oral		Silent		Oral		Silent	
	M	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*
Single-Fixation Duration	363.52	81.19	330.16	79.30	339.93	67.41	311.85	67.11
First-Fixation Duration	336.47	61.27	312.37	66.09	317.24	52.01	297.44	54.19
Total Fixation Duration	322.63	54.14	306.36	58.33	309.19	46.67	290.04	50.89
Refixation Duration	281.17	77.39	258.10	78.15	268.64	66.64	248.90	76.64
Fixations Per Word	1.40	.31	1.30	.29	1.44	.29	1.36	0.29
Refixation Probability	.10	.04	.10	.04	.10	.04	.10	.04
Rereading Duration	311.91	63.71	311.92	66.71	307.25	49.24	289.06	60.07
Gazes Per Word	.92	.12	.87	.14	.91	.11	.91	.13
Interword Regression Probability	.33	.09	.32	.08	.36	.09	.31	.10

Note. *M* = mean and *SD* = standard deviation.

Table 6

ANOVA Summary Table

	Grade	Reading Mode	Interaction
Single-Fixation Duration	*F*(1, 488) = 10.94, *p* = .001, η2 = .022	*F*(1, 488) = 145.81, *p* = <.001, η2 = .230	--
First-Fixation Duration	*F*(1, 488) = 11.40, *p* < .001, η2 = .023	*F*(1, 488) = 132.19, *p* = <.001, η2 = .213	--
Total Fixation Duration	*F*(1, 488) = 10.58, *p* = .001, η2 = .021	*F*(1, 488) = 123.37, *p* = <.001, η2 = .202	--
Refixation Duration	*F*(1, 488) = 3.61, *p* = .058, η2 = .007	*F*(1, 488) = 31.91, *p* = <.001, η2 = .061	--
Fixations Per Word	*F*(1, 488) = 3.59, *p* = .060, η2 = .007	*F*(1, 488) = 51.63, *p* = <.001, η2 = .096	--
Refixation Probability	*F*(1, 488) = .33, *p* = .569, η2 = .001	*F*(1, 488) = .10, *p* = .749, η2 = .000	--
Rereading Duration	*F*(1, 488) = 7.94, *p* = .005, η2 = .016	*F*(1, 488) = 11.79, *p* = <.001, η2 = .024	*F*(1, 488) = 11.76, *p* =<.001, η2 = .024
Gazes Per Word	*F*(1, 488) = 2.28, *p* = .131, η2 = .005	*F*(1, 488) = 16.90, *p* = <.001, η2 = .033	*F*(1, 488) = 30.40, *p* = <.001, η2 = .059
Interword Regression Probability	*F*(1, 488) = 2.36, *p* = .125, η2 = .005	*F*(1, 488) = 44.45, *p* = <.001, η2 = .078	*F*(1, 488) = 9.56, *p* = .002, η2 = .019

Note. Spaces with -- indicate that the information was not applicable.

For the single-fixation duration, first-fixation duration, and total fixation duration variables, significant main effects were found for grade and reading modality (see Table 6). However, the grade by modality interactions were not statistically significant. As expected, fourth graders exhibited longer single-fixation durations, first-fixation durations, and total fixation durations compared to fifth graders when reading. Similarly, students generally engaged in shorter fixations when reading silently compared to when they read orally. Furthermore, these orthographic processing variables, which reflect early stages of reading, were found to exhibit small but consistent effects for grade, whereas large effects were found for reading modality.

For the refixation duration and number of fixations per word eye-tracking measures, significant main effects were found for reading modality but not for grade. The grade by modality interactions were also not statistically significant. When reading silently, students engaged in shorter refixation durations and engaged in fewer fixations per word compared to when they read orally. For the refixation probability variable, no differences were found based on grade or reading modality, indicating that students generally exhibited similar probabilities of refixating on a word despite reading modality. Therefore, the three lexical processing variables were not affected by students' grade level, and refixation probability was comparable across late elementary schoolers regardless of oral and silent reading. However, silent reading was characterized by shorter refixations and fewer fixations per word, with a medium effect for modality on refixation duration and large effects for number of fixations per word.

Statistically significant interactions were found for grade and reading modality across the rereading duration, number of gazes per word, and interword regression probability variables. Examination of simple effects indicated that fifth graders exhibited significantly shorter durations of rereading words when reading silently ($p < .001$) compared to oral reading, whereas fourth graders' rereading durations were nearly identical despite reading modality (see Figure 1a). Engagement in oral reading, but not silent, led to a higher probability of making interword regressions for fifth graders only ($p = .003$) (see Figure 1b). However, fourth graders exhibited significantly fewer gazes during silent reading as compared to oral reading ($p < .001$), whereas fifth graders engaged in a similar number of gazes per word across reading modality (see Figure 1c). Higher-order processing variables, or skills reflecting later stages of processing, were affected by modality and grade level in a more nuanced manner. Silent reading may have yielded benefits in terms of efficiency for fourth and fifth grade students, as fourth graders unexpectedly had fewer gazes per word and fifth graders experienced shorter rereading durations. Due to complexities associated with silent reading measures, it is difficult to conclude why fourth graders exhibited fewer gazes per word. Although not explicitly studied in the literature, it is possible that fourth graders in this sample rushed through passages when reading silently. Finally, it was also unexpected that more interword regressions were made by fifth graders during oral reading as opposed to silent, indicating evidence of advanced reading processes during both reading modalities for students.

Figure 1. ANOVA Interaction Effects for Grade and Reading Modality

Figure 1a.

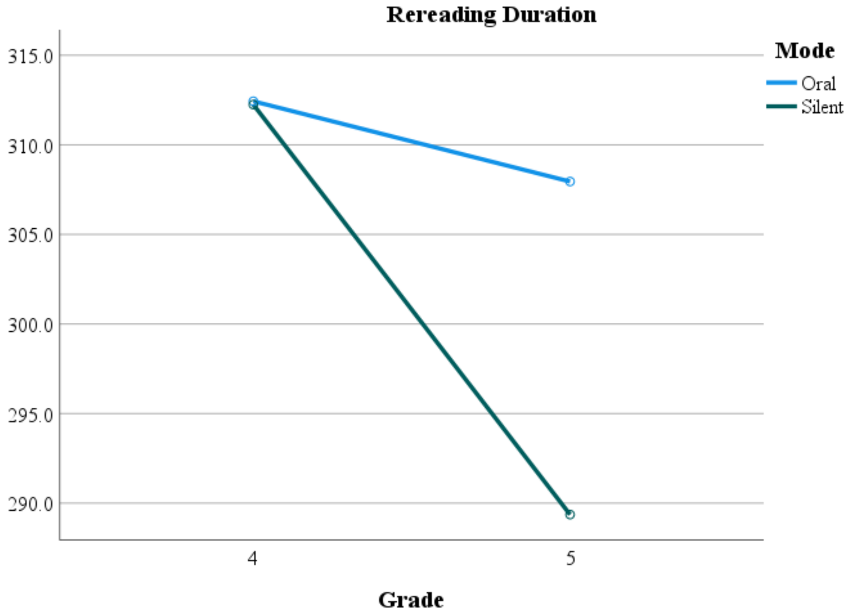


Figure 1b.

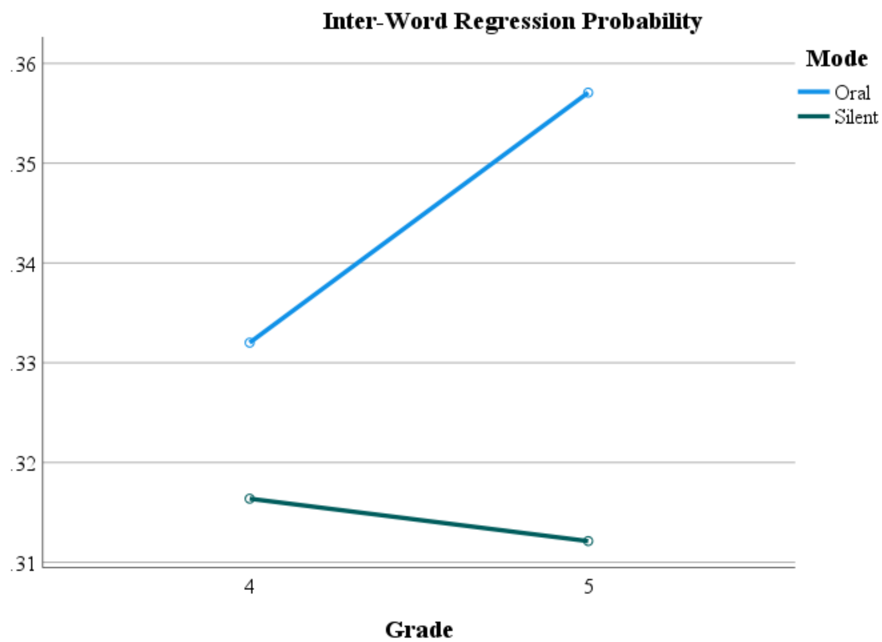
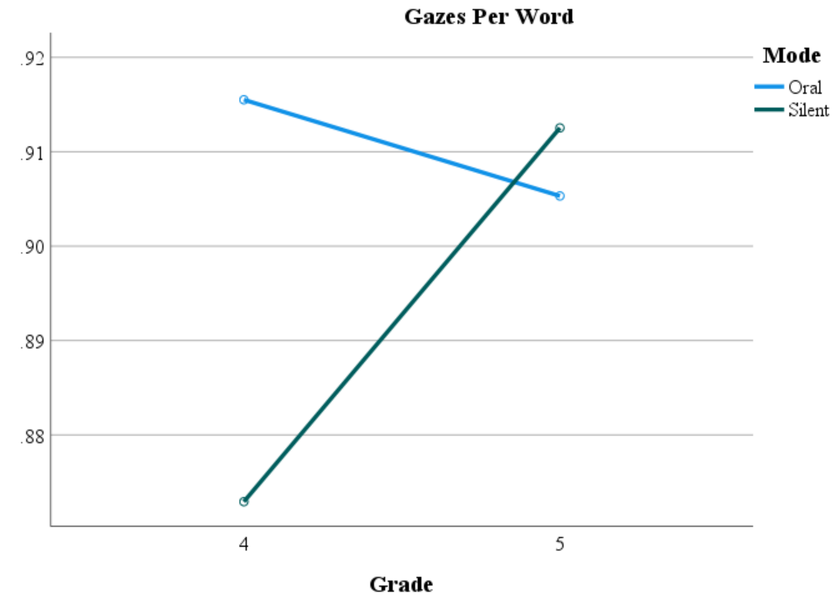


Figure 1c.



Structural Equation Modeling

Confirmatory Factor Analysis

Confirmatory factor analyses (CFA) were used to examine the sufficiency of the proposed measurement models (see Figure 2) prior to constructing the structural models (see Figure 3a & 3b). Based on the prior literature (Kim et al., 2019), a four-factor solution was initially hypothesized, with eye movement indicators loading on three latent factors including Orthographic Processing (i.e., single-fixation duration, first-fixation duration, and total fixation time), Lexical/Semantic Processing (i.e., refixation duration, number of fixations per word, and refixation probability), and Higher-Order Integration Processing (i.e., rereading duration, number of gazes per word, and interword regression probability) factors, and a Reading Comprehension factor (i.e., i-Ready vocabulary, literature, and informational text scores). However, as previously discussed, first-fixation duration and total fixation duration consistently yielded extremely high correlations with several other eye movement variables across grade and modality and were dropped from the model. Interword regression probability was found to exhibit nonsignificant or weak correlations with the two other variables comprising the proposed latent factor and was also removed.

After the deletion of the single-fixation duration, total fixation duration, and interword regression probability variables due to the described correlation issues, it was necessary to respecify the measurement model from a four-factor to a three-factor model. The Orthographic Processing latent factor was not viable as two of the three proposed indicators were dropped due to extreme multicollinearity (single-fixation duration and total fixation duration). The Higher-Order Integration factor was left with two of its proposed indicators, initial rereading duration and number of gazes per word variables, after interword regression probability variable was dropped. Interword regression probability was replaced by first-fixation duration in the respecified Higher-Order Integration factor. No changes were made to the Lexical/Semantic Processing or Reading Comprehension latent factors.

The three-factor model (two Eye Movement factors and the Reading Comprehension factor) yielded an inadmissible solution for all four models. MPlus provided a warning statement that the latent variable covariance matrix was a not positive definite, which occurred because the correlation between the two latent Eye Movement factors exceeded plausible values (i.e., 1.0). In sum, the a priori model based on the adult literature (e.g., Engbert et al., 2002; Kliegl & Laubrock, 2017; Reichle et al., 2003; Yang, 2006) was not supported. These results are similar to the failed models found with first graders in the Kim et al. (2019) study. It should be noted that the Reading Comprehension latent variable upheld an appropriate single factor for both grades, and it was only when the Eye Movement factors were added that the measurement model failed.

Exploratory Factor Analysis

Consistent with the procedure adopted by Kim et al. (2019), due to the inadmissible model found from the two-factor eye movement solution and the overall limited amount of eye-tracking studies with early readers, exploratory factor analyses (EFA) were performed to examine the factor structures for oral and silent reading among fourth and fifth graders. All nine of the eye movement variables were included in the EFAs. Prior to analyses, 50% of the participants were randomly selected using the sample randomization function in SPSS to create two subsamples for each grade. One subsample was used to conduct the EFA and the second was used as a validation sample to determine if the structure identified by the EFA could be replicated as a CFA. The EFAs were conducted using 143 students in grade four and 101 students in grade five. Maximum likelihood factor extraction method was used for the EFAs, and the promax (oblique) rotation was used to allow for correlations between the factors. The subsequent methods were used to determine the number of factors to extract included minimum eigenvalues of one (Kaiser, 1960), inspection of the scree plot for the inflection point, and three or more indicator loadings on each factor. Although factor loadings as low as >.30 are sometimes permissible (Child, 2006), in accordance with Kline (2023) a more stringent criteria of factor loading of .70 was considered ideal or good fit.

Across all four EFAs, the factor determination metrics converged on a one-factor solution. These results support a unidimensional Eye Movement factor for oral and silent reading across both fourth and fifth grade. Initially, the oral reading models for both fourth and fifth grade yielded inadmissible solutions due to Heywood cases stemming from the total fixation duration variable. Once this variable was removed, the model yielded a viable one-factor solution. Upon examination of all four EFAs, the single-fixation duration and first-fixation duration variables yielded loadings between .92 and .99 across both grades for oral and silent reading. Total fixation duration also presented a high loading for fourth (.96) and fifth (.97) grade silent reading. Additionally, rereading duration yielded factor loadings that approached or exceeded the .70 threshold, with values between .63 to .73 across grades and modality. Factor loadings for refixation duration, number of fixations per word, and number of gazes per word exceeded .3 but did not reach acceptable limits, whereas refixation probability and interword regression probability generally yielded factor loadings below even that minimal standard. Factor loading estimates for all EFAs can be reviewed in Table 7

Table 7

Standardized Factor Loadings for EFAs

Variable	Grade 4: Oral	Grade 4: Silent	Grade 5: Oral	Grade 5: Silent
Single-Fixation Duration	.92	.96	.97	.97
First-Fixation Duration	.95	.99	.95	.99
Total Fixation Duration	--	.96	--	.97
Refixation Duration	.46	.54	.48	.57
Fixations Per Word	.31	.45	.45	.43
Refixation Probability	.16	.35	-.01	.28
Rereading Duration	.73	.70	.63	.67
Gazes Per Word	.41	.57	.46	.64
Interword Regression Probability	.06	-.31	.19	-.29

Note. Spaces with -- indicate that the variable was removed from analyses.

Based on findings from the EFAs, four CFAs comprised of the unidimensional Eye Movement factor and the Reading Comprehension factor were conducted using the remaining sample of 134 fourth graders and 112 fifth graders. In accordance with the minimum factor loading criteria discussed above, only indicators that consistently yielded factor loadings which approached or exceeded .70 were retained for the final CFAs (Kline, 2023). Therefore, first-fixation duration, total fixation duration, and rereading duration were retained and used to produce the Eye Movement latent factor in the CFA using the replication samples. It should be noted that refixation duration was initially included as an indicator in the silent model for both grades, but that it resulted in an admissible solution (i.e., a Heywood case with factor loadings exceeded 1.0) and was removed from the models.

Model fit statistics suggest that all four of the two-factor measurement models consisting of the Eye Movement and Reading Comprehension latent factors fit the data adequately (see Table 8). All three indicators were found to significantly load onto the Eye Movement factor across reading modalities for both grades with values that exceeded the .70 threshold in all but one instance (see Table 9). Consistent with the EFA results, single-fixation duration and first-fixation duration presented high loadings (>.88) for both grades and reading modalities. Rereading duration also loaded well across the models (>.70), although the factor loading for this indicator fell below the ideal threshold for the fifth-grade silent reading model (.62). The Reading Comprehension latent variable demonstrated appropriate factor structure across both oral and silent reading models for the fourth- and fifth-grade data, with loadings ranging between .82 and .91. Standardized factor loadings are presented in Table 9. Modification indices, factor loadings, and standardized residuals were examined for possible revisions to improve model fit.

After review of modification indices, there were no further theoretically sound changes available that would significantly improve the mode.

Table 8

Model Fit Indices for Final CFAs

	X^2 (df, *p*-value)	CFI	RMSEA (90% CI)	SRMR	AIC	BIC
Fourth Grade: Oral Reading	10.81 (8, .213)	.99	.05 (.00, .12)	.03	4622.52	4677.58
Fourth Grade: Silent Reading	24.36* (8, .002)	.97	.12 (.07, .18)	.05	4552.00	4607.05
Fifth Grade: Oral Reading	15.00 (8, .060)	.99	.09 (.00, .16)	.03	3731.11	3782.76
Fifth Grade: Silent Reading	7.32 (8, .503)	1.00	.00 (.00, .11)	.02	3793.30	3844.95

Note. **$p < .01$

Table 9

Standardized Factor Loadings for Final CFA

Factor/loading	Grade 4: Oral	Grade 4: Silent	Grade 5: Oral	Grade 5: Silent
Eye Movement Factors				
Single-Fixation Duration	.96***	.88***	.97***	.96***
First-Fixation Duration	.97***	.90***	.97***	.97***
Rereading Duration	.75***	.82***	.70***	.62***
Reading Comprehension				
i-Ready Vocabulary	.82***	.82***	.82***	.82***
i-Ready Literature	.91***	.91***	.91***	.91***
i-Ready Informational Text	.88***	.88***	.91***	.91***

Note. All factor loadings were statistically significant, *p* < .001.

Structural Models

Once the measurement model was identified, structural models were analyzed to explore the relations among the Eye Movement factor, Reading Comprehension factor, and WCPM or WPM (which was an observed variable) to represent oral and silent reading fluency. The structural relations among the factors were analyzed across separate models to represent oral and silent reading modalities (see Figures 4a and 4b) and by grade level. The contributions of the Eye Movement factor to the Reading Comprehension factor and WCPM/WPM were examined through direct and indirect relations. WCPM/WPM also served as a direct predictor of the Reading Comprehension variable. The final structural models for oral reading among fourth and fifth graders generally fit the data well (see Table 10 for fit statistics). However, model fit for the oral reading among fifth graders was marginal, with RMSEA values falling above acceptable limits. However, elevated values for this statistic are common when the sample size is small, as was the case for the fifth-grade replication sample (n = 112) (Hu & Bentler, 1999). For the fourth-grade silent reading model, modification indices suggested freeing the residual correlation between the single- and first-fixation duration indicators, which was allowed due to theoretical soundness.

Figure 4. Final Structural Models

Figure 4a.

Fourth Grade Oral Reading

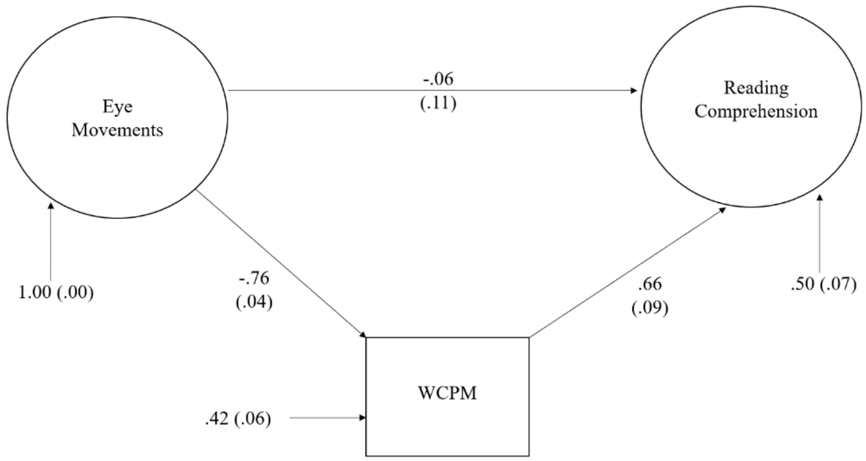


Figure 4b.

Fourth Grade Silent Reading

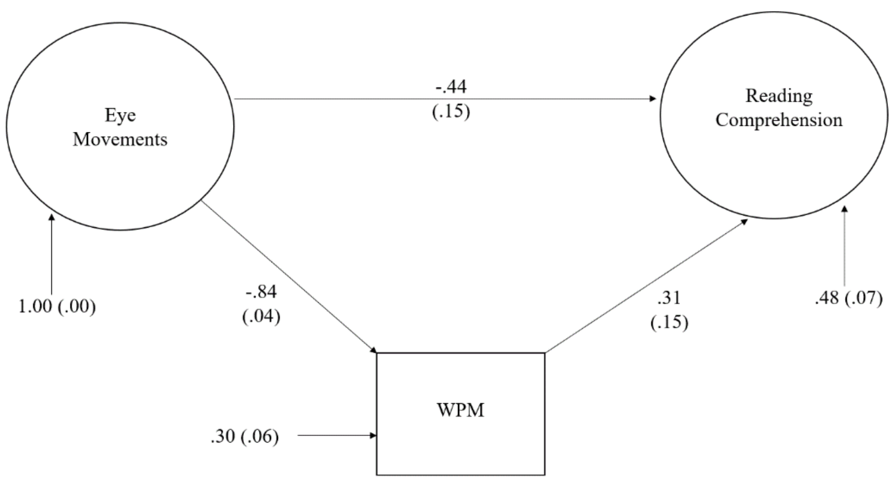


Figure 4c.

Fifth Grade Oral Reading

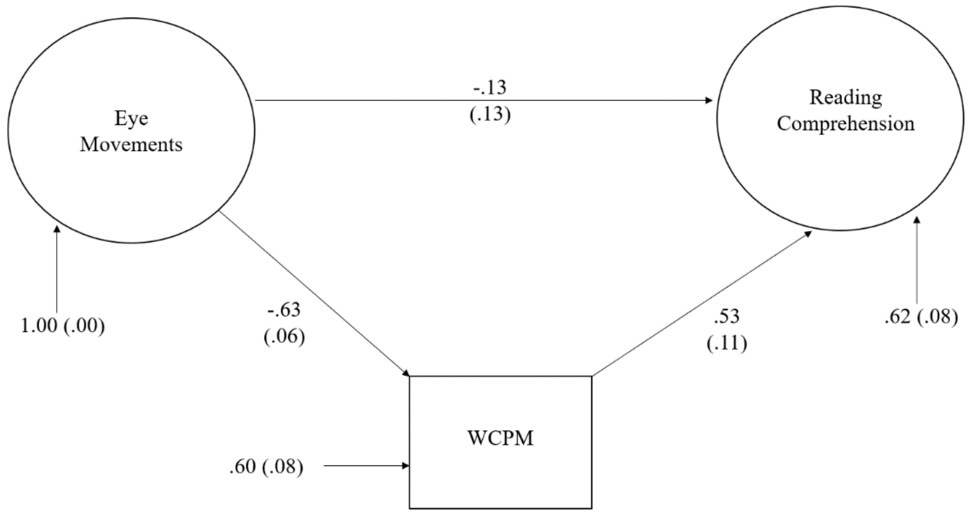


Figure 4d.

Fifth Grade Silent Reading

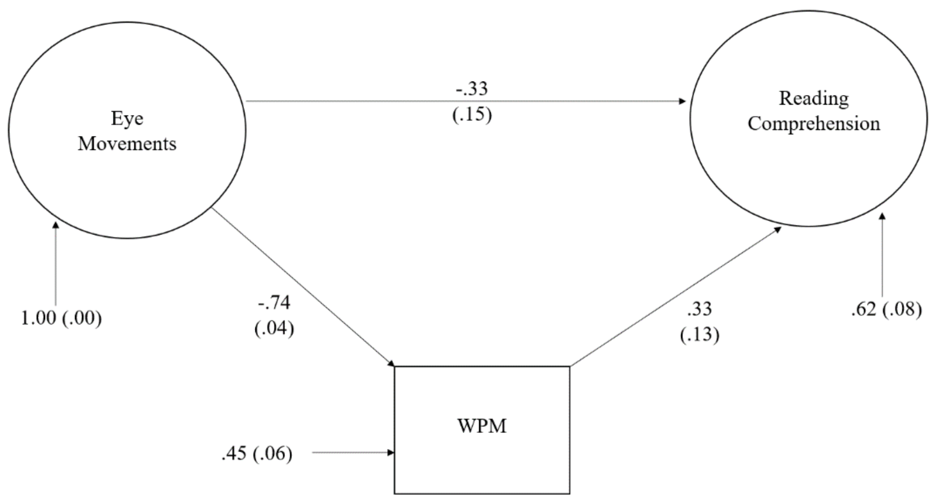


Table 10

Model Fit Indices for Final Structural Model

	X^2 (df, *p*-value)	CFI	RMSEA (90% CI)	SRMR	AIC	BIC
Fourth Grade: Oral Reading	16.69 (12, .162)	.99	.05 (.00, .11)	.03	5211.48	5278.13
Fourth Grade: Silent Reading	16.47 (11, .125)	.99	.06 (.00, .12)	.03	5199.94	5269.49
Fifth Grade: Oral Reading	39.02* (12, .000)	.96	.14 (.09, .19)	.03	4242.74	4305.26
Fifth Grade: Silent Reading	14.09 (12, .295)	1.00	.04 (.00, .11)	.02	4358.99	4421.52

Note. *$p < .001$

Standardized path coefficients were reported for each structural model (see Table 11). Consistent with Kline (2023), standardized coefficient effect sizes at or above .05 are considered small, values above .15 are moderate, and those above .25 are interpreted as large. For the oral reading models, results indicated that Eye Movements did not have a direct effect on Reading Comprehension latent variables across grades four (-.06) and five (-.13). However, there was a significant negative indirect effect for grades four (-.51) and five (-.34). This suggests that the Eye Movement factor had a large effect on Reading Comprehension, but the influence of Eye Movements was made through its role in supporting oral reading fluency, as measured by WCPM. The Eye Movement factor was found to have a direct effect on WCPM for grades four (-.76) and five (-.63), and this was the strongest association within the oral reading model. Faster reading rate is characteristic of lower durations of variables within the Eye Movement variable, so negative relations with WCPM and Reading Comprehension were expected. Finally, as would be anticipated, WCPM had a large direct effect on Reading Comprehension across both grades

Table 11

Standardized Direct, Indirect, and Total Effects for Oral and Silent Reading Models

	Oral Reading Model					
	Grade 4			Grade 5		
	Direct	Indirect	Total	Direct	Indirect	Total
Reading Comprehension						
Eye Movements	-.06	-.51***	-.57***	-.13	-.34***	-.47***
WCPM	.66***	--	.66***	.53***	--	.53***
WCPM						
Eye Movements	-.76***	--	-.76***	-.63***	--	-.63***
	Silent Reading Model					
	Grade 4			Grade 5		
	Direct	Indirect	Total	Direct	Indirect	Total
Reading Comprehension						
Eye Movements	-.44**	-.26*	-.70***	-.33*	-.25*	-.58***
WPM	.31*	--	.31*	.33**	--	.33**
WPM						
Eye Movements	-.84***	--	-.84***	-.74***	--	-.74***

Note. * $p < .05$, ** $p < .01$, *** $p < .001$.

In contrast to the results from the oral reading model, all path coefficients within the silent reading model were significant for both grades ($p < .001$). The strongest relation within the silent reading model was negative for Eye Movements and WPM for grades four (-.84) and five (-.74), whereas relations between WPM and Reading Comprehension were found to be positive but smaller for fourth (.31) and fifth (.33) graders. Next, significant direct relations were found for the Eye Movements and Reading Comprehension variables for fourth (-.44) and fifth graders (.33), and the indirect relations were slightly weaker but consistent between both grades (-.26 and -.25, respectively). The oral and silent models explained approximately 48% of the variance in Reading Comprehension in fourth grade and 38% of the variance was accounted for in Reading Comprehension among fifth graders.

In sum, although the paths, or relations, within the oral and silent reading models were largely comparable, noteworthy differences were found between the two models. Only the silent reading model included a direct effect of Eye Movements on Reading Comprehension, and this was found for both grades. Additionally, direct effects of the WPM variable were less pronounced on Reading Comprehension (.31 & .32) compared to effects from the WCPM measure (.66 & .53) which can likely be explained by the role of reading errors in the WCPM. variable, as well as the larger role of Eye Movements in silent versus oral reading.

Discussion

The goal of this study was to better understand the function of eye movements during oral and silent reading, and how specific eye movement behaviors relate to reading comprehension. Few studies with children have considered both oral and silent reading modalities across the past 10 years (e.g., Foster et al., 2018; Kim et al., 2019; Kim et al., 2022; Krieber et al., 2017; Vorstius et al., 2013). This study included a normative sample of fourth and fifth graders whose oral and silent reading fluency skills were assessed using benchmark passages, as well as additional measures of reading comprehension. All eye movement data variables were selected with the consideration of typical word-level measures explored in prior research (e.g., Foster et al., 2018; Kim et al., 2019; Krieger et al., 2013; Sperlich et al., 2015; Yan et al., 2013).

The first aim of this study was to examine eye movement differences during oral versus silent reading, and whether differences exist based on grade level. Based on the literature, it is known that once children have become fluent readers, oral reading can hinder skills among advanced readers (Chall, 1983, 1996; Prior et al., 2011). It is understood that oral reading is characteristic to the reliance on eye-voice coordination, which causes constraints such as longer and more frequent fixations (Ashby et al., 2012; Vorstius et al., 2014). Furthermore, it was hypothesized that eye movement characteristics during oral and silent reading would differ, with fifth graders demonstrating more strategic reading behavior during silent reading. Specific eye movement behaviors in this study consisted of single-fixation durations, first-fixation duration, total fixation time, and refixation duration, number of fixations per word, refixation probability per word, rereading duration, number of gazes per word, and interword regression probability. Eye movement comparisons were then examined based on grade level and reading modality.

Grade level and reading modality affected students' single-fixation duration, first-fixation duration, and total fixation duration. Eye-tracking research has postulated that fixation duration reflects the early stages of word processing (Foster et al., 2018). Fourth graders were generally found to yield longer single-, first-, and total fixation durations when reading compared to fifth graders, which is consistent with previous studies. Word processing skills advance over time, leading to more advanced skills reflected by shorter and fewer fixations when reading

(McConkle et al., 1991; Valle et al., 2013). Lexical/semantic processing skills are thought to be captured by frequencies of regressions and probability of fixating and skipping words (Foster et al., 2018). Students exhibited fewer and shorter fixations when reading silently for both grades, indicating that lexical/semantic skills were more efficient during silent reading, as it was not slowed by the production of speech. These findings also overlap with those by Kim et al. (2022), as their participants were found to exhibit a higher number of fixations and longer fixation durations when reading orally. Therefore, these results align with the prior literature suggesting that the transition from oral to silent reading is underway when students are in the fourth grade or late elementary school, making oral reading less beneficial (Chall, 1983, 1996; Prior et al., 2011).

The probability of refixating on words was not related to modality or grade level, as approximately 10 % of words were refixated despite grade level or modality. This finding contradicts prior literature demonstrating that more advanced readers would engage in fewer refixations when reading (Huestegge et al., 2009; Hutzler & Wimmer, 2004; McConkie et al., 1991; Valle et al., 2013). When interpreting this result, it is important to consider that the frequencies and durations of fixations fluctuate as readers develop skills, as well as with the changing difficulty of text (Rayner et al., 2006). Within this realm, studies focusing on word frequency effects suggest that when words are encountered more often, they become easier to read compared to less common words (Foster et al., 2018; Valle et al., 2013). This study utilized grade-level benchmark passages which were designed to be accessible to readers with a range of skills and consisted of primarily high frequency words (see Table 1). Although the examination of word frequency effects was outside the scope of this work, the passages used in this study included more high-frequency words, which could have led to a similar amount of refixations from all readers. Overall, future eye-tracking research should prioritize examination of passage characteristics such as word frequency, as these factors may contribute to differences in eye movement behaviors between grades.

Interactions between reading modality and grade level were found for rereading duration, number of gazes per word, and the probability of making interword regressions, indicating that these specific eye movement behaviors during reading can be predicted by level of reading development and engagement in oral versus silent reading. Notably, these variables were also grouped together in the proposed higher-order integration latent factor examined later in this section. For rereading duration, reading modality yielded meaningful differences for only students in fifth grade, as rereading durations were significantly shorter during silent reading. This outcome aligns with initial hypotheses, as prior literature has found that students in fifth grade read faster during silent rather than oral reading (Rayner, 1998). Fourth graders are assumed to have less developed reading skills and are likely to spend more time rereading words compared to fifth graders (McConkle et al., 1991; Valle et al., 2013). Next, only fourth graders exhibited significantly fewer gazes per word based on reading modality, which was observed during silent reading. It is not surprising that evidence of more strategic eye movements was associated with silent reading. However, this finding contradicts assumptions that more advanced readers (i.e., fifth graders) would exhibit more developed skills. For example, a recent longitudinal study by Kim et al. (2022) demonstrated that rereading duration and gazes per word were found to decrease as skills developed over time during both oral and silent reading for first through third graders. Finally, it was also surprising to find that the probability of making interword regressions was higher for fifth graders when reading orally. It is commonly understood that interword regressions are related to availability of cognitive resources

(McConkie et al., 1991) and are indicative of higher reading skill. Although it was expected that more advanced readers would exhibit this result, it was assumed that this would occur during silent reading, as it is known that oral reading constrains skills due to the dependence on eye-voice coordination (Vorstius et al., 2014).

Overall, findings imply that eye movements within the orthographic, lexical/semantic, higher-order integration processes vary based on grade level and reading modality. As expected, orthographic processing skills were less developed for fourth graders compared to those in fifth grade, and many of the other eye movement variables evidenced more advanced skills for fifth graders and/or the silent reading modality. However, eye movements within the lexical/semantic and higher-order integration domains presented unexpected findings based on grade and reading modality, suggesting the need for additional research.

Another goal of this study was to understand underlying factor structures of eye movements and to explore how these reading behaviors contribute to oral and silent reading fluency and reading comprehension. The current study aimed to focus on late-elementary readers' eye movements, as the only other study utilizing SEM approaches with elementary-aged students focused on first graders (e.g., Kim et el., 2019). Although many of the same variables were examined, it is important to note that Kim et al. (2019) used the EyeMap technology by Tang et al. (2012) to capture eye movements and had access to skills not analyzed in this study (e.g., initial landing position, number of fixations in gaze). It was assumed that SEM analyses would demonstrate three Eye Movement factors including orthographic processing, lexical/semantic processing, and higher-order integration which represent advanced skills observed in adult readers (e.g., Engbert et al., 2002; Reichle et al., 2003; Yang, 2006). Although these factors did not emerge in the study by Kim et al. (2019), it was hypothesized that fourth and fifth graders would exhibit this three-factor structure, as their reading skills are assumed to be transitioning towards the level of adults. It was also proposed that reading fluency would make significant contributions to reading comprehension across both modalities and grade levels based on existing research with late-elementary aged students (e.g., Dickens & Meisinger, 2017; Price et al., 2015; Prior et al., 2011; Robinson et al., 2018). However, consistent with results from Kim et al. (2019), this study did not yield the initially hypothesized three-factor structure. This outcome suggests that late-elementary school students' eye movement behaviors are not yet adultlike, and that their reading skills are still constrained by the bottleneck of decoding processes in early stages of reading (Sperlich et al., 2016). Therefore, exploratory approaches were then adopted to better understand eye movements during reading among children.

Several variables in this study demonstrated extremely high or low correlations (see Tables 5 and 6), making it necessary to respecify the initial three-factor solution as two factors, with Reading Comprehension as the third latent factor. First-fixation duration and total fixation time were highly correlated with other variables outside of their proposed factor structure, whereas interword regression probability was not correlated with its variable group. These trends suggest that relations among certain eye movement skills in late-elementary school students do not align with those observed among adults. Despite these modifications, the two-factor Eye Movement solution yielded inadmissible findings for oral and silent reading in grades four and five. Considering the previous work by Kim et al. (2019) is the only other study that has explored the factor structure of eye movements in children, EFAs using only the eye movement variables were then conducted due to determine whether a factor structure could be reliability identified. Both grades were split into randomized halves prior to conducting EFAs so that findings could be validated through use of CFAs on the other 50% of the sample. EFAs were also conducted among the first-grade sample from Kim et al. (2019), yielding a 10-factor model prior to specifying the bi-factor solution. Results of all four exploratory analyses in this study yielded a one-factor solution for oral and silent reading for both grades. Three variables consistently demonstrated strong factor loadings, including single-fixation duration, first fixation duration, and rereading duration, all of which reflect early reading skills. These results were replicated on the other 50% of the sample through CFAs consisting of a unidimensional Eye Movement factor and the Reading Comprehension latent factor. Overall, the unidimensional structures resulting from the EFAs continue to support that early reading skills overlap compared to those of adult readers.

Structural relations among the Eye Movement factor, the Reading Comprehension factor, and WCPM as an observed variable were then modeled separately by grade level and reading modality. Congruent with reading studies focusing on students in late elementary school (e.g., Dickens & Meisinger, 2017; Price et al., 2015; Prior et al., 2011; Robinson et al., 2018), it was predicted that eye movements and reading fluency skills would be related to reading comprehension within both modalities for fourth and fifth graders. For example, in Kim et al. (2019), eye movements were associated with word reading and comprehension among highly skilled readers in the beginning of the year, but this was not seen among struggling readers. Additionally, after examining the effects of comprehension skills on reading rate, Vorstius et al. (2014) indicated that children with slower reading speeds also demonstrated weaker comprehension skills.

Findings from structural models suggest that the initial theory that Eye Movements, reading fluency, and Reading Comprehension demonstrate meaningful relations among late-elementary school students. In this sample, relevant eye movements were first-fixation duration, single-fixation duration, and rereading duration. Collectively, these eye movements were indirectly, but not directly, related to Reading Comprehension for fourth and fifth graders when reading orally. However, during silent reading, Eye Movements were directly and indirectly related to Reading Comprehension, with smaller associations for the indirect relations. These findings suggest that shorter durations among the three indicators indirectly led to better Reading Comprehension performance. Next, the strongest relations in both the oral and silent reading modality models were between Eye Movements and WCPM/WPM, indicating that regardless of reading modality, shorter Eye Movement durations yielded faster reading fluency skills. These findings make sense given the that lower durations indicate faster reading speed. The direct effects of WPM on Reading Comprehension for silent reading were less pronounced than for WCPM on Reading Comprehension during oral reading. Overall, although a direct effect of Eye Movements was found only for silent reading, the relations among the paths in the models were largely comparable.

Results of this study indicate that eye movements are related to level of reading development and reading modality. As would be expected, orthographic processing skills were less developed among fourth graders, as they exhibited longer single-, first-, and total fixations. Lexical/semantic skills (e.g., refixation duration, fixations per word), although similar for both grades, were more advanced during silent reading, whereas refixation probability was not dependent on grade level or modality likely due to use of high frequency words in the passage All higher-order integration skills exhibited interactions for grade and modality, although some findings did not directly support hypotheses. As expected, silent reading predicted shorter rereading durations among fifth graders and fewer gazes per word among fourth graders, whereas the probability of making interword regressions was higher for fifth graders when reading orally. Next, the initially proposed three higher-order indexes discussed above did not fit the data, and a unidimensional factor comprised of single-fixation duration, first-fixation duration, and rereading duration was found instead, which suggests that the eye movements of late elementary schoolers are not yet comparable to those of adults. Consistent with the broader literature, results demonstrated meaningful relations with reading fluency and reading comprehension skills. Eye movements and reading fluency (WCPM/WPM) yielded the strongest relations across both reading modalities, illustrating that shorter durations of eye movement behaviors predict higher fluency skills. Shorter eye movement durations also predicted higher reading comprehension skills, especially when reading silently, whereas oral reading was characteristic of more pronounced effects of WCPM on reading comprehension. Therefore, although not consistently, many findings were congruent with initial assumptions about reading behaviors. Given that such minimal prior research exists addressing this study's aims, more work is needed to develop a thorough understanding of the role of eye movements during oral and silent reading, and how these factors relate to reading comprehension.

Limitations & Future Directions

The current study examined word-level eye movement differences based on reading modality between fourth and fifth graders. Although this study paved a new direction in the eye-tracking research by focusing on young readers, several limitations and future directions should be acknowledged. Although the literature related to text features at the passage- and individual word-level (e.g., word length, frequency, difficulty) was reviewed and details of the passages used in this study were presented, text features were not considered in hypotheses or analytical approaches. This study utilized grade-level benchmark passages not designed specifically for this study, as this created a more realistic and ecologically valid context given the aim to understand typical reading development. However, this did not allow for manipulation of these potentially important text features or to standardization of passages. It is possible that some of this study's findings are related to the nature of the passages used, such as proportions of longer versus shorter words, word frequency, and passage length all likely affect subsequent eye movements (Kim et al., 2022). Similarly, per Foster et al. (2018), the probabilities of fixating and skipping words are considered indicators of readers' lexical processing skills, and it is likely that word characteristics uniquely determine these behaviors. For example, fifth graders in this study unexpectedly exhibited more interword regressions during oral instead of silent reading. It was also surprising that fourth graders rather than students in fifth grade demonstrated significantly fewer gazes per word during silent reading. Therefore, further questions remain related to specific word characteristics and any associated trends in readers' gaze, regressions, and other eye movement behaviors such as word skipping during oral versus silent reading.

Another limitation of this study is the lack of focus on readers' individual differences and proficiency levels. Results of Kim et al. (2019) concluded that reading proficiency was a moderate predictor of the relations between eye movements and first grade students' reading skills, such that specific eye movements were indicative of different levels of reading performance. In their longitudinal study examining eye movement behaviors from first through third grade, Kim et al. (2022) also found that individual differences in reading proficiency largely accounted for changes in skill acquisition across time. Furthermore, future studies should consider readers' individual skill differences rather than focusing on grade level as the only indicator for ability level. A similar approach should be adopted when examining reading comprehension, as the role of individual differences found by Keenan et al. (2008) contrasts past research trends which have consistently viewed reading comprehension as one broad skill. The choice of reading comprehension measures may also impact results, as research suggests that some measures reflect basic reading or decoding skills more than others (e.g., Cutting, et al. 2006). Therefore, further comparisons among various reading comprehension measures and subskills should be examined with an added consideration of the role of reading modality.

SEM techniques were also utilized to fill research gaps about eye movements during reading, and how these reading behaviors relate to reading comprehension. Given that this has not yet been explored in eye-tracking or reading modality literature, this study was exploratory in nature, and questions remain related to factor structure of eye movements. Furthermore, there is a general need for more eye-tracking studies employing SEM techniques, as these analytical approaches provide unique and necessary information about skill domains of interest in the research (e.g., orthographic processing, lexical/semantic processing, higher-order integration processing). Finally, future studies should also employ measurement invariance testing to determine if latent factor structures remain consistent across grades to address further uncertainties related to oral and silent reading skill development.

Conclusion

Despite the limitations discussed above, this study provided insight into future directions needed within eye-tracking research, a growing literature that provides meaningful and specific information related to reading skills. Given that most eye-tracking research has focused on adult readers, gaps exist related to specific reading behaviors among children during the transition from oral to silent reading in elementary school. Although Kim et al. (2019) examined reading behaviors during oral and silent reading in first graders using structural equation modeling techniques, the current study was the first to examine eye movements among fourth and fifth graders using eye-tracking technology. The use of structural modeling provided impactful insights into the exact relations between eye movements, reading comprehension, and reading fluency, and how these relations differ as a function of grade and reading modality. This work also aimed to address the lack of studies comparing reading modality differences on reading comprehension skills. Considering the complicated and unclear nature of specific eye movements exhibited during reading, substantial effort is needed to better understand this topic in the reading literature.

References

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

Ashby, J., Rayner, K., & Clifton, C. (2005). Eye movements of highly skilled and average readers: Differential effects of frequency and predictability. *The Quarterly Journal of Experimental Psychology Section A,* 58, 1065–1086. https://doi.org/10.1080/ 02724980443000476

Ashby, J., Yang, J., Evans, K. H. C., & Rayner, K. (2012). Eye movements and the perceptual span in silent and oral reading. *Attention, Perception, & Psychophysics, 74,* 634–640.

Bayram, S., Camnalbur, M., & Esgin, E. (2012). Analysis of dyslexic students' reading disorder with eye movement tracking. *Cypriot Journal of Educational Sciences, 7,* 129–148.

Bentler, P. M. (1990). Comparative fit indexes in structural models. *Psychological Bulletin, 107,* 238-246. http://dx.doi.org/10.1037/0033-2909.107.2.238

Blanchard, H. E., Pollatsek, A., & Raynet K. (1989). The acquisition of parafoveal word information in reading. *Perception & Psychophysics, 46,* 85-94.

Blythe, H. I., & Joseph, H. S. S. L. (2011). Children's eye movements during reading. In S.P. Liversedge, I. D. Gilchrist, & S. Everling (Eds.), The Oxford handbook of eye movements (pp. 801–818). Oxford University Press.

Blythe, H. I., Liversedge, S. P., Joseph, H. S. S. L., White, S. J., & Rayner, K. (2009). Visual information capture during fixations in reading for children and adults. *Vision Research, 49,* 1583–1591.

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

Brysbaert, M., & Vitu, F. (1998). Word skipping: Implications for theories of eye movement control in reading. In Eye guidance in reading and scene perception (pp. 125-147). Elsevier Science Ltd.

Carpenter, P. A., & Just, M. A. (1983). What your eyes do while your mind is reading. In K. Rayner (Ed.), Eye movements in reading: Perceptual and language processes (pp. 275-307). Academic Press.

Chall, J. S. (1983). Stages of reading development. McGraw-Hill.

Chall, J. S. (1996). Learning to read: The great debate (Rev. ed.). McGraw-Hill.

Chard, D.J., Vaughn, S., & Tyler, B.J. (2002). A synthesis of research on effective interventions for building reading fluency with elementary students with learning disabilities. *Journal of Learning Disabilities, 35,* 386–406. https://doi.org/10.1177/00222194020 350050101

Child, D. (2006). The essentials of factor analysis. A&C Black.

Christ, T. J., White, M. J., Ardoin, S. P., & Eckert, T. L. (2013). Curriculum based measurement of reading: Consistency and validity across best, fastest, and question reading conditions. *School Psychology Review, 42*, 415-436.

Clifton, C., Staub, A., & Rayner, R. (2007). Eye movements in reading words and sentences. In R. van Gompel, M. Fischer, W. Murray, & R. Hill (Eds.). Eye movements: A window on mind and brain (pp. 341–372). Elsevier.

Collins, A. A., Lindström, E. R., & Compton, D. L. (2018). Comparing students with and without reading difficulties on reading comprehension assessments: A meta-analysis. *Journal of Learning Disabilities, 51,* 108-123. https://doi.org/10.1177/0022219417704636.

Collins, A. A., Lindström, E. R., & Sandbank, M. (2021). The influence of language knowledge

and test components on reading comprehension scores. *Annals of Dyslexia, 71,* 238–259. https://doi.org/10.1007/s11881-020-00212-y

Colón, E. P., & Kranzler, J. H. (2006). Effect of instructions on curriculum-based measurement of reading. *Journal of Psychoeducational Assessment, 24,* 318-328.

Curriculum Associates. (2018). i-Ready assessments technical manual: March 2018.

Cutting, L. E., & Scarborough, H. S. (2006). Prediction of reading comprehension: Relative contributions of word recognition, language proficiency, and other cognitive skills can depend on how comprehension is measured. *Scientific Studies of Reading, 10,* Article 3.

David, H. A., Hartley, H. O., & Pearson, E. S. (1954). The distribution of the ratio, in a single normal sample, of range to standard deviation. *Biometrika, 41*, 482–493. https://doi.org/10.2307/2332728

De Luca, M., Di Pace, E., Judica, A., Spinelli, D., & Zoccolotti, P. (1999). Eye movement patterns in linguistic and non-linguistic tasks in developmental surface dyslexia. *Neuropsychologia, 37,* 1407–1420. https://doi.org/10.1016/S0028-3932(99)00038-X

Dickens, R. H., & Meisinger, E. B. (2015). Examining the effects of skill level and reading modality on reading comprehension. *Reading Psychology, 37*, 318–337. https://doi.org/10.1080/02702711.2015.1055869

Dickens, R. H., & Meisinger, E. B. (2016). Examining the effects of skill level and reading modality on reading comprehension. *Reading Psychology*, *37*, 318–337.

Dickens, R. H., & Meisinger, E. B. (2017). Examining the effects of reading modality and passage genre on reading comprehension in middle school students. *Reading Psychology, 38*, 321–347. https://doi.org/10.1080/02702711.2016.1263701

Elgart, D. B. (1978). Oral reading, silent reading, and listening comprehension: A comparative study. *Journal of Reading Behavior, 10,* 203–207.

Engbert, R., Longtin, A., & Kliegl, R. (2002). A dynamic model of saccade generation in reading based on spatially distributed lexical processing. *Vision Research, 42,* 621-636. https://doi.org/10.1016/S0042-6989(01)00301-7

Faul, F., Erdfelder, E., Lang, A.-G., & Buchner, A. (2007). G*Power 3: A flexible statistical power analysis program for the social, behavioral, and biomedical sciences. *Behavior Research Methods, 39,* 175-191.

Fletcher, J., & Pumfrey, P. D. (1988). Differences in text comprehension amongst 7-8 year old students. *School Psychology International, 9*, 133–145. https://doi.org/10.1177/0143034388092008

Foster, T. E., Ardoin, S. P., & Binder, K.S. (2013). Underlying changes in repeated reading: An eye movement study. *School Psychology Review, 42*, 140–156.

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

Frazier, L., & Rayner, K. (1982). Making and correcting errors during sentence comprehension: Eye movements in the analysis of structurally ambiguous sentences. *Cognitive Psychology, 14*, 178–210.

Fuchs, L.S., Fuchs, D., Hosp, M.K., & Jenkins, J.R. (2001). Oral reading fluency as an indicator of reading competence: A theoretical, empirical, and historical analysis. *Scientific Studies of Reading, 5*, 239–256. https://doi.org/10.1207/S1532799XSSR0503_3

Haenggi, D., & Perfetti, C. A. (1994). Processing components of college-level reading comprehension. *Discourse Processes, 17*, 83-104.

Hale, A. D., Skinner, C. H., Williams, J., Hawkins, R. O., Neddenriep, C. E., & Dizer, J. (2007). Comparing comprehension following silent and aloud reading across elementary and secondary students: Implications for curriculum-based measurement. *The Behavior Analyst Today, 8*, 9–23. https://doi.org/10.1037/ h0100101

Hausbrouck, J., & Tindal, G. A. (2006). Oral reading fluency norms: A valuable assessment tool for reading teachers. *The Reading Teacher, 59*, 636–644. https://doi.org/10.1598/RT.59.7.3

Hiebert, E. H., Samuels, S. J., & Rasinski, T. (2012). Comprehension-based silent reading rates: What do we know? What do we need to know? *Literacy Research and Instruction, 51*, 110–124. https://doi.org/10.1080/19388071.2010.531887

Hiebert, E. H., Wilson, K. M., & Trainin, G. (2010). Are students really reading in independent reading contexts? An examination of comprehension-based silent reading rate. In E. H. Hiebert & D. R. Reutzel (Eds.), Revisiting silent reading (pp. 151-167). International Reading Association.

Hu, L. & Bentler, P. M. (1999). Cutoff criteria for fit indexes in covariance structure analysis: Conventional criteria versus new alternatives. *Structural Equation Modeling: A Multidisciplinary Journal, 6*, 1-55.

Huestegge, L., Radach, R., Corbic, D., & Huestegge, S.M. (2009). Oculomotor and linguistic determinants of reading development: A longitudinal study. *Vision Research, 49*, 2948–2959. https://doi.org/10.1016/j.visres.2009.09.012

Hutzler, F., & Wimmer, H. (2004). Eye movements of dyslexic children when reading in a regular orthography. *Brain and Language, 89,* 235–242. https://doi.org/10.1016/S0093-934X(03)00401-2

IBM Corp. Released 2019. IBM SPSS Statistics for Windows, Version 26.0. IBM Corp.

Inhoff, A. W. (1984). Two stages of word processing during eye fixations in the reading of prose. *Journal of Verbal Learning and Verbal Behavior, 23*, 612–624.

Inhoff, A. W., Connine, C., Eiter, B., Radach, R., & Heller, D. (2004). Phonological representation of words in working memory during sentence reading. *Psychonomic Bulletin & Review, 11*, 320-325.

Inhoff, A. W., & Radach, R. (1998). Definition and computation of oculomotor measures in the study of cognitive processes. In G. Underwood (Ed.), Eye guidance in reading and scene perception (pp. 29–54). Elsevier.

Inhoff, A. W., & Rayner, K. (1986). Parafoveal word processing during eye fixations in reading: Effects of word frequency. *Perception & Psychophysics, 40,* 431–439.

Inhoff, A. W., Solomon, M., Radach, R., & Seymour, B. (2011). Temporal dynamics of the eye voice span and eye movement control during oral reading. *Journal of Cognitive Psychology, 23*, 543-558.

Joseph, H. S. S. L., Nation, K., & Liversedge, S. P. (2013). Using eye movements to investigate word frequency effects in children's sentence reading. *School Psychology Review, 42*, 207-222. https://doi.org/10.1080/02796015.2013.12087485

Just, M. A., & Carpenter, P. A. (1980). A theory of reading: From eye fixations to comprehension. *Psychological Review, 87,* 329–354. https://doi.org/10.1037/0033-295X.87.4.329

Keenan, J. M., Betjemann, R. S., & Olson, R. K. (2008). Reading comprehension tests vary in the skills they assess: Differential dependence on decoding and oral comprehension. *Scientific Studies of Reading, 12,* 281-300. https://doi.org/10.1080/10888430802132279

Kim, Y. S. G., Little, C., Petscher, Y., & Vorstius, C. (2022). Developmental trajectories of eye movements in oral and silent reading for beginning readers: A longitudinal investigation. *Scientific Reports, 12*. https://doi.org/10.1038/s41598-022-23420-5

Kim, Y. S. G., Petscher, Y., & Vorstius, C. (2019). Unpacking eye movements during oral and silent reading and their relations to reading proficiency in beginning readers. *Contemporary Educational Psychology, 58*, 102-120. https://doi.org/10.1016/j.cedpsych.2019.03.002

Kim, Y., Wagner, R. K., & Foster, E. (2011). Relations among oral reading fluency, silent reading fluency, and reading comprehension: A latent variable study of first-grade readers. *Scientific Studies of Reading, 15*, 338–362. https://doi.org/10.1080/108 88438.2010.493964

Kliegl, R., & Laubrock, J. (2017). Eye-movement tracking during reading. In A. M. B. de Groot & P. Hagoort (Eds.). Research methods in psycholinguistics (pp. 68–88). Wiley.

Kline, R. B. (2023). Principles and practice of structural equation modeling (5th ed.). Guilford Press.

Kragler, S. (1995). The transition from oral to silent reading. *Reading Psychology, 16*, 395–408. https://doi.org/10.1080/0270271950160402

Krieber, M., Bartl-Pokorny, K. D., Pokorny, F. B., Zhang, D., Landerl, K., Körner, C., Pernkopf, F., Pock, T., Einspieler, C., & Marschik, P. B. (2017). Eye movements during silent and oral reading in a regular orthography: Basic characteristics and correlations with childhood cognitive abilities and adolescent reading skills. *PloS one, 12,* e0170986.

Kuhn, M. R., & Schwanenflugel, P. J. (2007). Fluency in the classroom. Guilford Press.

Kuhn, M. R., Schwanenflugel, J. P., & Meisinger, E. B. (2010). Aligning theory and assessment of reading fluency: Automaticity, prosody, and definitions of fluency. *Reading Research Quarterly, 45*, 230-251. https://doi.org/10.1598/RRQ.45.2.4

LaBerge, D., & Samuels, S. J. (1974). Toward a theory of automatic information processing in reading. *Cognitive Psychology*, *6*, 293–323. https://doi.org/10.1016/0010-0285(74)90015-2

Lundberg, I. (1994). The teaching of reading. In W. B. Elley (Ed.), The IEA study of reading literacy: Achievement and instruction in thirty-two school systems (pp. 149-192). Pergamon.

Mason, L., Pluchino, P., & Tornatora, M.C. (2013). Effects of picture labeling on science text processing and learning: Evidence from eye movements. *Reading Research Quarterly, 48*, 199–214. https://doi.org/10.1002/rrq.41

McConkie, G. W., Kerr, P. W., Reddix, M. D., & Zola, D. (1988). Eye movement control during reading: I. The location of initial eye fixations in words. *Vision Research*, *28*, 1107–1118.

McConkie, G. W., Kerr, P. W., Reddix, M. D., Zola, D., & Jacobs, A. M. (1989). Eye movement control during reading: II. Frequency of refixating a word. *Perception and Psychophysics, 46*, 245–253.

McConkie, G. W., & Rayner, K. (1975). The span of the effective stimulus during a fixation in reading. *Perception & Psychophysics, 17*, 578-586.

McConkie, G. W., Zola, D., Grimes, J., Kerr, P. W., Bryant, R. B., & Wolff, P. M. (1991). Children's eye movements during reading. In J.F. Stein (Ed.), Vision and visual dyslexia (pp. 251–262). Macmillan.

Miller, B., & O'Donnell, C. (2013). Opening a window into reading development: Eye movements' role within a broader literacy research framework. *School Psychology Review, 42*, 123–140.

Miller, S. D., & Smith, D. E. (1990). Relations among oral reading, silent reading and listening comprehension of students at differing competency levels. *Reading Research and Instruction, 29*, 73–84.

Muthén, L. K., & Muthén, B. O. (2017). Mplus: Statistical analysis with latent variables: User's guide (8th ed.). Muthén & Muthén.

Nation, I. S. P. (2016). Making and using word lists for language learning and testing. John Benjamins Publishing Company.

National Reading Panel. (2000). Report of the national reading panel. Washington, DC: Author.

O'Regan, J. K. (1981). The convenient viewing position hypothesis. In D. F. Fisher, R. A. Monty, & J. W. Senders (Eds.). Eye movements: Cognition and visual perception (pp. 289–298). Erlbaum.

Pikulski, J. J., & Chard, D. J. (2005). Fluency: Bridge between decoding and reading comprehension. *International Reading Association, 58*, 510–519. https://doi.org/10.1598/RT.58.6.2

Price, K. W., Meisinger, E. B., D'Mello, S. K., & Louwerse, M. M. (2012). Silent reading fluency using underlining: Evidence for an alternative method of assessment. *Psychology in the Schools, 49,* 606–618.

Price, K. W., Meisinger, E. B., Louwerse, M. M., & D'Mello, S. (2015). The contributions of oral and silent reading fluency to reading comprehension. *Reading Psychology, 37,* 167-201. https://doi.org/10.1080/02702711.2015.1025118

Prior, S. M., Fenwick, K. D., Saunders, K. S., Ouellette, R., O'Quinn, C., & Harvey, S. (2011). Comprehension after oral and silent reading: Does grade level matter? *Literacy Research and Instruction, 50,* 183–194. https://doi.org/10.1080/193880 71.2010.497202

Prior, S. M., & Welling, K. A. (2001). "Read in your head": A Vygotskian analysis of the transition from oral to silent reading. *Reading Psychology, 22,* 1–15. https://doi.org/10.1080/0270271 0151130172

Pynte, J., & Kennedy, A. (2006). An influence over eye movements in reading exerted from beyond the level of the word: Evidence from reading English and French. *Vision Research, 46,* 3786–3801.

Radach, R., Huestegge, L., & Reilly, R. (2008). The role of global top-down factors in local eye movement control during reading. *Psychological Research, 72,* 675–688.

Radach, R., & Kempe, V. (1993). An individual analysis of initial fixation positions in reading. In G. d'Ydewalle, & J. Van Rensbergen (Eds.). Perception and cognition: Advances in eye movement research (pp. 213–226).

Radach, R., & Kennedy, A. (2004). Theoretical perspectives on eye movements in reading: Past controversies, current issues and agenda for future research. *European Journal of Cognitive Psychology, 16,* 3–26. https://doi.org/10.1080/09541440340000295

Radach, R., Schmitten, C., Glover, L., & Huestegge, L. (2009). How children read for comprehension: Eye movements in developing readers. In R. K. Wagner, C. Schatschneider, & C. Phythian-Sence (Eds.) Beyond decoding: The behavioral and biological foundations of reading comprehension (pp. 75–106). Guilford Press.

Rayner, K. (1975). The perceptual span and peripheral cues in reading. *Cognitive Psychology, 7*, 65–81. https://doi.org/10.1016/0010-0285(75)90005-5

Rayner, K. (1979). Eye guidance in reading: fixation locations within words. *Perception, 8*, 21–30.

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

Rayner, K., Ardoin, S.P., & Binder, K.S. (2013). Children's eye movements in reading: A commentary. *School Psychology Review, 42*, 223–233.

Rayner, K., Chace, K. H., Slattery, T. J., & Ashby, J. (2006). Eye movements as reflections of comprehension processes in reading. *Scientific Studies of Reading, 10*, 241–255. https://doi.org/10.1207/ s1532799xssr1003_3

Rayner, K., & Duffy, S. A. (1986). Lexical complexity and fixation times in reading: Effects of word frequency, verb complexity, and lexical ambiguity. *Memory & Cognition, 14*, 191-201.

Rayner, K., Fischer, M. H., & Pollatsek, A. (1998). Unspaced text interferes with both word identification and eye movement control. *Vision Research, 38*, 1129–1144.

Rayner, K., & Pollatsek, A. (1987). Eye movements in reading: A tutorial review. In M. Coltheart (Vol. Ed.), Attention and performance. Vol. 12. Attention and performance (pp. 327–362). Erlbaum.

Rayner, K. & Pollatsek, A. (1989). Reading psychology. Hillsdale, NJ: Lawrence Erlbaum

Reichle, E. D., Rayner, K., & Pollatsek, A. (2003). The E_Z reader model of eye-movement control in reading: Comparisons to other models. *Behavior and Brain Sciences, 26,* 445–476.

Reilly, R., & Radach, R. (2006). Some empirical tests of an interactive activation model of eye movement control in reading. *Cognitive Systems Research, 7,* 34–55.

Reschly, A. L., Busch, T. W., Betts, J., Deno, S. L., & Long, J. D. (2009). Curriculum-based measurement oral reading as an indicator of reading achievement: A meta-analysis of the correlational evidence. *Journal of School Psychology, 47*, 427–469. https://doi.org/10.1016/j.jsp.2009.07.001

Robinson, M. F., & Meisinger, E. B. (2021). The relation among phonological processing, oral and silent reading fluency, and reading comprehension for students with dyslexia: A longitudinal investigation. *Reading & Writing Quarterly: Overcoming Learning Difficulties, 38*, 1-18. https://doi.org/10.1080/10573569.2021.1972880

Robinson, M. F., Meisinger, E. B., & Joyner, R. E. (2018). The influence of oral versus silent reading on reading comprehension in students with reading disabilities. *Learning Disability Quarterly, 42,* 105-116. https://doi.org/10.1177/0731948718806665

Sabatini, J., Wang, Z., & O'Reilly, T. (2019). Relating reading comprehension to oral reading performance in the NAEP fourth-grade special study of oral reading. *Reading Research Quarterly, 54*, 253-1271 https://doi.org/10.1002/rrq.226

Schimmel, N., & Ness, M. (2017). The effects of oral and silent reading on reading comprehension. *Reading Psychology, 38*, 390–416.

Schwanenflugel, P. J., & Knapp, N. F. (2016). The psychology of reading: Theory and applications. Guilford Press.

Seimyr, G. Ö. (2021). The Science of Lexplore. Technical note. Lexplore: Stockholm, Sweden. https://doi.org/10.5281/zenodo.5595803

Share, D. L. (2008). On the anglocentricities of current reading research and practice: The perils of overreliance on an “outlier” orthography. *Psychological Bulletin, 134*, 584–615. https://doi.org/10.1037/0033-2909.134.4.584

Sperlich, A., Meixner, J., & Laubrock, J. (2016). Development of the perceptual span in reading: A longitudinal study. *Journal of Experimental Child Psychology, 146*, 181–201.

Sperlich, A., Schad, D. J., & Laubrock, J. (2015). When preview information starts to matter: Development of the perceptual span in German beginning readers. *Journal of Cognitive Psychology, 27*, 511–530.

Steiger, J. H. (1990). Structural model evaluation and modification: An interval estimation approach. *Multivariate Behavioral Research, 25*, 173–180.

Steiger, J. H. & Fouladi, R. T. (1997). Noncentrality interval estimation and the evaluation of statistical models. In L. L. Harlow, S. A. Mulaik & J. H. Steiger (Eds.), What if there were no significance tests? (pp. 221-257). Lawrence Erlbaum.

Stuart, M., Dixon, M., Masterson, J., & Gray, B. (2003). Children's early reading vocabulary: Description and word frequency lists. *British Journal of Educational Psychology, 73*, 585-598.

Sweet, A., & Snow, C. (Eds.). (2003). Rethinking reading comprehension. Guilford Press.

Tabachnick, B. G., & Fidell, L. S. (2019). Using multivariate statistics (7th ed.). Pearson.

Tang, S., Reilly, R. G. & Vorstius, C. (2012). EyeMap: A software system for visualizing and analyzing eye movement data in reading. *Behavior Research Methods*, *44*, 420–438. https://doi.org/10.3758/s13428-011-0156-y

Tinker, M.A. (1936). Reliability and validity of eye-movement measures of reading. *Journal of Experimental Psychology, 19*, 732– 746. https://doi.org/10.1037/h0060561

Torgesen, J. K. (2005). Recent discoveries on remedial interventions for children. In M. J. Snowling & C. Hulme (Eds.), The science of reading: A handbook (pp. 521–537). Blackwell.

Turkyılmaz, M., Can, R., Yildirim, K., & Ates, S. (2014). Relations among oral reading fluency, silent reading fluency, and reading comprehension. *Procedia - Social and Behavioral Sciences*, *116,* 4030–4034. https://doi.org/10.1016/j.sbspro.2014.01.885

Valle, A., Binder, K. S., Walsh, C. B., Nemier, C., & Bangs, K. E. (2013). Eye movements, prosody, and word frequency among average and high skilled second grade readers. *School Psychology Review, 42,* 171–190.

Vitu, F., O'Regan, J. K., Inhoff, A.W. & Topolski, R. (1995). Mindless reading: Eye movement characteristics are similar in scanning letter strings and reading texts. *Perception and Psychophysics, 57,* 352-364.

Vorstius, C., Radach, R., Mayer, M. B., & Lonigan, C. J. (2013). Monitoring local comprehension monitoring in sentence reading. *School Psychology Review, 42,* 191–206. https://doi.org/10.1080/13506285.2014.881445

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

Vygotsky, L. S. (1978). Mind in society: The development of higher psychological processes (M. Cole, V. John-Steiner, S. Scribner, & E. Souberman, Eds.). Harvard University Press.

Wang, L. C. (2020). The relationships among temporal processing, rapid naming, and oral reading fluency in Chinese children with and without dyslexia. *Learning Disability Quarterly, 43*, 167-178.

Wayman, M. M., Wallace, T., Wiley, H. I., Tichá, R., & Espin, C. A. (2007). Literature synthesis on curriculum-based measurement in reading. *The Journal of Special Education, 41*, 85-120.

White, S. J. (2007). Foveal load and parafoveal processing: The case of word skipping. In R. van Gompel, M. Fischer, W. Murray, & R. Hill (Eds.). Eye movements: A window on mind and brain (pp. 409–424). Elsevier.

White, S., Sabatini, J., Park, B. J., Chen, J., Bernstein, J., & Li, M. (2021). The 2018 NAEP Oral Reading Fluency study (NCES 2021-025). Institute of Education Sciences, National Center for Education Statistics, U.S. Department of Education. https://nces .ed.gov/pubsearch/pubsinfo.asp?pubid=2021025

Wilkinson, I. A. G., & Anderson, R. C. (1995). Sociocognitive processes in guided silent reading: A microanalysis of small-group lessons. Reading Research Quarterly, 30, 710–740.

Yang, S.-N. (2006). An oculomotor-based model of eye movements in reading: The competition/interaction model. *Cognitive Systems Research, 7,* 56–69.

Zeno, S. M., Ivens, S. H., Millard, R. T., & Duvvuri, R. (1995). The educator's word frequency guide. Touchstone Applied Science Association.