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The Relations of Online Reading Processes (Eye Movements) with Working Memory, Emergent Literacy Skills, and Reading Proficiency

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ABSTRACT

We examined the relations between working memory, emergent literacy skills (e.g., phonological awareness, orthographic awareness, rapid-automatized naming), word reading, and listening comprehension to online reading processes (eye movements), and their relations to reading comprehension. A total of 292 students were assessed on working memory and emergent literacy skills in Grade 1, and eye movements, language, and reading skills in Grade 3. Structural equation model results showed that word reading was related to gaze duration and rereading duration, but listening comprehension was not. Working memory and emergent literacy skills were related to eye movements, but their relations to eye movements were largely mediated by word reading. Eye movements were related to reading comprehension, but not after accounting for word reading and listening comprehension. These results expand our understanding of reading development by revealing the nature of relations of emergent literacy skills, reading, and listening comprehension to online processes.

Reading requires the interaction of visual, linguistic, and cognitive systems (Liversedge, Gilchrist, & Everling, 2011; Perfetti & Stafura, 2014; Radach & Kennedy, 2004). In the last four decades, reading skills as well as language and cognitive predictors of reading skills have been studied intensively, using *off-line measurements* (e.g., students' performance on comprehension questions after reading passages). Another rich line of work has focused on underlying *online processes* during reading. In particular, eye-tracking technology has been widely used to investigate and reveal online reading processes (e.g., Inhoff & Radach, 1998; Rayner, 1998, 2009; Reichle, 2015). Although both lines of work have provided critical insights about reading development, there are at least two gaps. First, the vast majority of eye-tracking studies have been conducted with adult proficient readers; thus, there is a limited understanding of eye movements in developing readers, who may show different patterns of online processes relative to proficient readers (e.g., see Blythe & Joseph, 2011; Henry, Van Dyke, & Kuperman, 2018; Kim, Petscher, & Vorstius, 2019; Vorstius, Radach, & Lonigan, 2014; Yan, Pan, Laubrock, Kliegl, & Shu, 2013). Second, research on reading processes and reading skills has been largely conducted in disparate lines of work, although reading processes and skills should be related. In the present study, we addressed these gaps in the literature by examining online processes using eye-tracking for developing readers, and by both investigating eye movements (online processes) and skills (working memory, emergent literacy, and reading skills) in the same participants.

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Skills that contribute to reading

According to the simple view of reading and associated robust evidence, reading comprehension requires word reading and listening comprehension (e.g., Adlof, Catts, & Little, 2006; Hoover & Gough, 1990; Joshi, Tao, Aaron, & Quiroz, 2012; Kim, 2015, 2017; Tunmer & Chapman, 2012). Word reading, in turn, draws on emergent skills such as phonological awareness, orthography (letter knowledge and orthographic awareness), and lexical and sublexial semantics (e.g., morphological awareness) (Adams, 1990; Deacon, Kirby, & Casselman-Bell, 2009; Kim, Apel, & Al Otaiba, 2013; National Center for Family Literacy, 2008; National Institute of Child Health and Human Development [NICHD], 2000; Torgesen, Wagner, & Rashotte, 1994; Wolter, Wood, & D'zatko, 2009). Listening comprehension draws on language skills such as vocabulary and grammatical/syntactic knowledge as well as higher-order cognitive skills such as inference-making skills and comprehension monitoring (e.g., Alonzo, Yeomans-Maldonado, Murphy, & Bevens, 2016; Florit, Roch, & Levorato, 2014; Kendeou, Bohn-Gettler, White, & van den Broek, 2008; Kim, 2015, 2016; Kim & Phillips, 2014; Lepola, Lynch, Laakkonen, Silvén, & Niemi, 2012; Tompkins, Guo, & Justice, 2013). In addition, working memory is foundational for reading and skills that contribute to reading such as phonological awareness, morphological awareness, vocabulary, and listening comprehension (Daneman & Merikle, 1996; Florit et al., 2014; Hoien-Tengesdal & Tonnessen, 2011; Kim, 2015, 2016; Kim, 2017; Kim & Phillips, 2014; Swanson & Howell, 2001).

According to the direct and indirect effects model of reading (DIER; Kim, 2017, 2020a, 2020b), these multiple skills have hierarchical relations such that word reading and listening comprehension are proximal skills for reading comprehension; word reading is supported by emergent literacy skills while listening comprehension is supported by language skills (i.e., vocabulary and grammatical knowledge) and higher-order cognitive skills (e.g., inference-making skills). In addition to its contribution to word reading, morphological awareness is related to vocabulary knowledge and grammatical knowledge, and therefore is also related to listening and reading comprehension via vocabulary and grammatical knowledge (e.g., Kim, Guo, Liu, Peng, & Yang, 2020). Finally, all these component skills and knowledge are supported by domain-general cognitive skills such as working memory and attentional control such that domain general cognitive skills contribute to reading comprehension via all the other component skills. Therefore, whether domain general cognitive skills are independently related to reading comprehension depends on what is accounted for in analytical models of these constructs (e.g., if higher-order skills are accounted for, working memory may not have a direct relation to reading comprehension Kim, 2020a, 2020b).

Online processes during reading

A large body of research has examined eye movements as indicators of online processes during reading based on the idea that eye movement patterns are driven by cognitive and attentional demands of a task that requires rapid and efficient coordination of multiple physiological and psychological processes (Just & Carpenter, 1976; Radach & Kennedy, 2013; Rayner, 1998; Reichle, 2015). A number of computational reading models have been developed to simulate reading patterns, taking into account known mechanisms of oculomotor control and linguistic processing. For example, authors of the E-Z reader (Reichle, Rayner, & Pollatsek, 2003) and SWIFT models (Engbert, Longtin, & Kliegl, 2002) hypothesize that word reading and associated orthographic, phonological, and semantic processes are the main driver of oculomotor-visual processing in reading. Although these models and others (e.g., GLENMORE by Reilly & Radach, 2006; Oculomotor-based model by Yang, 2006) differ to some extent, they all operate under the assumption that certain eye movement behaviors and their respective parameters are associated with specific underlying cognitive processes. Eye movement studies typically include a variety of different temporal (when to move the eyes to the next location) and spatial (where to direct the eyes to with the next movement) indicators to describe reading and underlying cognitive processes. The amount of time spent on a word, with one or multiple fixations, before leaving it for the first time (gaze duration), for example, is thought to capture the initial decoding process and lexical access (Inhoff, 1984; Inhoff & Radach, 1998; Rayner & Pollatsek, 1987). Further rereading of a word (rereading time; i.e., coming back to the word after having read one or multiple other words) is taken as an indicator of higher-order syntactic integration processes (Radach, Huestegge, & Reilly, 2008; Radach & Kennedy, 2004; Rayner, Chace, Slattery, & Ashby, 2006; but see Kliegl & Laubrock, 2017, for a dynamic view). Regarding spatial parameters, saccade amplitude is related to task difficulty (shorter saccades under higher difficulty, possibly related to a smaller perceptual span), which is relevant to developing readers (Blythe & Joseph, 2011; Rayner, 1998).

Previous experimental reading research with eye tracking was predominantly focused on word and text characteristics (e.g., word length or frequency; Rayner, 1998; Tiffin-Richards & Schroeder, 2015). In contrast, literature with respect to the relation between eye movements and individuals' skills is much scarcer, especially that including developmental data. The few extant studies have shown a relation between individuals' off-line skills and online processes measured by eye movements. For example, Ashby, Rayner, and Clifton (2005) found that online word reading processing differed as a function of reading comprehension proficiency in a sample of skilled versus average adult readers. Similarly, Chace, Rayner, and Well (2005) showed that less skilled adult reading comprehenders did not activate phonological codes of words that were visually available in the parafovea and overall were less able to obtain information from parafoveal preview (parafoveal processing) than skilled readers. Kuperman and Van Dyke (2011) found that RAN and word reading skill predicted and moderated the influence of word length and frequency on fixation times with an adolescent and adult sample (16–24 years old). Other recent studies using RAN letters and digits tasks (e.g., Henry et al., 2018; Pan, Yan, Laubrock, Shu, & Kliegl, 2013) found differences in parafoveal processing between typically developing readers and those with dyslexia. In a similar vein, better readers and spellers showed larger perceptual spans and made more use of parafoveal information compared to less skilled individuals (Veldre & Andrews, (2015, 2016), and Sperlich, Schad, and Laubrock (2015), (2016)) concluded that the efficient use of parafoveal information presupposes mastery of basic processes of reading, which in their German sample happened around second grade. Finally, Kim et al. (2019) found using data from English-speaking children that the nature of relations between eye movements and reading skill varied as a function of children's reading skill (both word reading and reading comprehension) such that the relations were weaker for poor readers in Grade 1 and stabilized in the spring for children whose reading skill was average and above.

Present study

Our goal in this study was to examine the relations between online processes (measured by eye movements) and reading (and related) measures, using data from beginning readers. Despite growing evidence about the relations between eye movements and reading skills (i.e., Connor et al., 2014; Kim et al., 2019; Sperlich, Meixner, & Laubrock, 2016; Yan et al., 2013), extant studies have primarily focused on RAN, word reading, and reading comprehension. Notably absent are studies of other well-known emergent literacy skills and studies of other relevant cognitive factors, such as working memory, particularly for young developing readers (see Kuperman & Van Dyke, 2011,; Stella & Engelhardt, 2019 for studies with adolescents and college students). Specific research questions were as follows: (1) How do working memory and emergent literacy skills (phonological awareness, orthographic awareness, morphological awareness, letter naming fluency, and RAN) relate to eye movements during connected text reading? (2) How are eye movements related to reading comprehension? (3) What is the nature of relations among eye movements, working memory, emergent literacy skills, word reading, listening comprehension, and reading comprehension? Are eye movements related to reading comprehension over and above word reading and listening comprehension? Do working memory and emergent literacy skills relate to eye movements after accounting for word reading and listening comprehension?

These questions were addressed using longitudinal data from English-speaking children in the United States where literacy instruction typically starts in kindergarten. Working memory and emergent literacy skills were assessed in Grade 1. The emergent literacy skills in the study were based on DIER (Kim, 2017, 2020a) and the triangle model (Adams, 1990) as well as a large body of studies indicating their roles (see above), and were assessed at the beginning of Grade 1 when majority students are considered novice readers. Eye movements (which measures reading comprehension processes), word reading, listening comprehension, and reading comprehension were measured at the end of Grade 3 when foundational reading skills are expected to have developed.

We chose three eye movement variables that are known to reflect online processes during reading and show development in beginning readers (e.g., Blythe & Joseph, 2011; Tiffin-Richards & Schroeder, 2015; Vorstius et al., 2014). Gaze duration, the time spent on a word before leaving it for the first time, is thought to reflect (earlier) processes including orthographic processing up to lexical access, whereas rereading time (total time spent on a word minus gaze duration) is an indicator for (later) processes related to higher-level processing like syntactic integration (Inhoff & Radach, 1998; Rayner, 1998). In addition to these two temporal variables, we included saccade amplitude (size of an eye movement between two fixations) as a spatial indicator, as it is known that with development, children make longer saccades (Blythe & Joseph, 2011; McConkie et al., 1991; Rayner, 1985; Vorstius et al., 2014).

We hypothesized that working memory and emergent literacy skills would be related to eye movement variables. Specifically, phonological awareness, letter naming fluency, orthographic awareness, and morphological awareness may be particularly relevant to gaze duration, which captures the initial orthographic process up to lexical access (Inhoff & Radach, 1998; Radach & Kennedy, 2004; Rayner, 1998). We also hypothesized that orthographic awareness, letter naming fluency, and RAN might be particularly implicated in parafoveal processing (see above) and may similarly relate to rereading duration. Working memory was hypothesized to be related to eye movements bivariately, but not after controlling for emergent literacy skills, aligned with the hierarchical relations hypothesis of DIER.

We expected that word reading would have strong relations with eye movements, based on the E-Z and SWIFT models (see above). We also speculated that listening comprehension may be related to gaze duration and rereading duration. Listening comprehension captures semantic processes as well as higher-level integration processes (Florit et al., 2014; Kendeou et al., 2008; Kim, 2016, 2017; Tompkins et al., 2013), and therefore, it would relate to gaze duration and rereading duration to the extent that these two eye movement indicators capture semantic and higher-order cognitive processes for developing readers (Radach et al., 2008; Rayner et al., 2006). Finally, we hypothesized that eye movement variables may not be independently related to reading comprehension once word reading and listening comprehension are accounted for because the relations of eye movements to reading comprehension may be largely shared with these skills – that is, the decoding and comprehension processes measured by the eye movement variables are captured in word reading and listening comprehension skills, which is in line with the simple view of reading and DIER. A schematic representation of structural relations is presented in Figure 1, which shows products (those in dark shades) and underlying processes (those in light shades) as well as their hypothesized relations examined in this study.

Method

Participants

Data in the present study are from a longitudinal study of students' reading development conducted in the Southeastern region of the US. The relations of emergent literacy skills to reading skills in Grade 1 were reported (Kim & Petscher, 2016). A total of 292 children were included in the study. The sample was composed of 52% male and predominantly White (60%), followed by Black (26%), Multi-racial (6%), Hispanic (6%), and Asian (2.5%) students. Fifty-two percent of students were eligible for free or

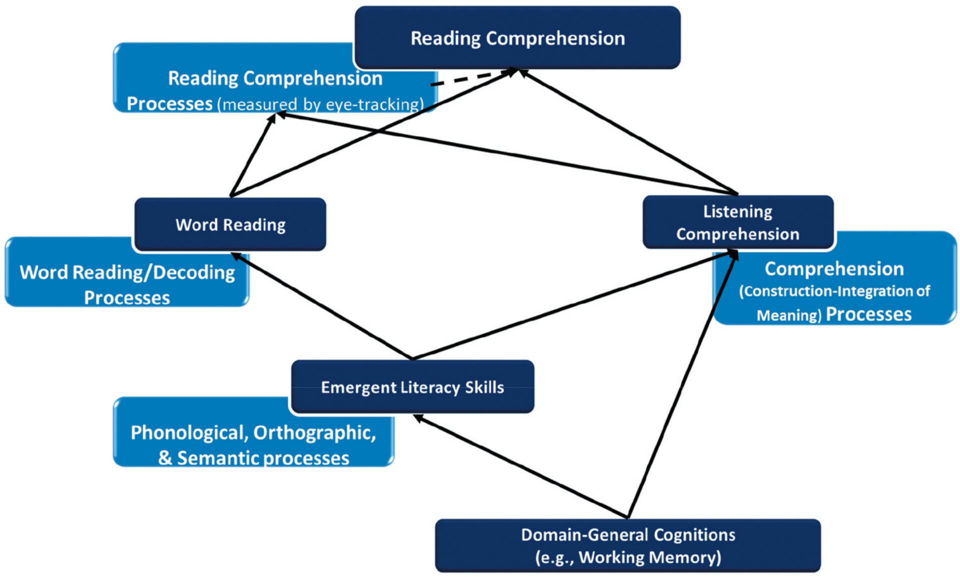

Figure 1. A schematic representation of conceptual model in this study that is aligned with the direct and indirect effects model of reading (Kim, 2017, 2020a, 2020b). Those in dark shades are products and those in light shades are underlying processes. The relation of emergent literacy skills to listening comprehension is primarily driven by the semantic processes that involves morphological awareness, and its relations to vocabulary and grammatical knowledge which contribute to listening comprehension (see Kim, 2020a, 2020b for details). The relations of eye-tracking to reading comprehension is posited to relate to reading comprehension, but its influence is posited to be largely shared with word reading and listening comprehension as indicated by a dashed line (see the hypothesis section).

reduced price lunch, 8% of students were receiving services (e.g., speech), and no students were identified as having limited English proficiency.

Missingness ranged from 0% on the Grade 3 eye movement data to 28% on the Grade 1 orthographic awareness measure.[1] Little's (1988) test of data missing completely at random (MCAR) resulted in rejection of the null hypothesis that data were MCAR, $\chi^2(143) = 195.41$, $p = .002$. A review of the data did not suggest the patterns of missing data were non-ignorable and as there are no vetted methods to empirically test that the data are missing at random, we thus assumed that the data were Missing At Random. As such, the MLR estimator was used to appropriately account for the missing data and non-normally distributed data (i.e., in the rereading duration) in the structural equation models (Enders, 2010).

Measures

Unless otherwise noted, all the items were administered and dichotomously scored (correct = 1; incorrect = 0). More information about offline measures are found in the online supplementary materials. Reliability estimates are reported in Table 1.

Online reading processes as measured by eye movements in Grade 3

Children were presented with three grade-level passages (292 to 307 words; one narrative text and two informational texts) and were asked to read aloud. Oral reading was shown to have stronger relations with offline reading skills for developing readers than for silent reading (e.g., Vorstius et al., 2014). These passages were normed in the state where the present study was conducted (see online supplementary materials).

Table 1. Descriptive statistics for manifest variables.

Measure	*N*	Reliability	Minimum	Maximum	Mean	SD	Skew	Kurtosis
G1 Working Memory	285	.65	0.00	9.00	2.73	1.82	0.33	−0.32
G1 Phonological Awareness	271	.90	0.00	20.00	8.04	4.19	0.95	0.76
G1 Phonological Awareness SS	271	NA	2	19	10.36	2.94	0.27	1.13
G1 Orthographic Awareness	209	.82	6.00	39.00	25.33	6.66	0.22	−0.46
G1 Morphological Awareness	270	.87	1.00	36.00	19.74	6.62	−0.10	−0.45
G1 Letter Naming Fluency	270	.86-.93*	7.00	104.00	58.00	15.49	0.12	0.70
G1 RAN	271	.97**	15.00	78.00	28.69	8.55	1.94	5.98
G3 Gaze Duration	292	NA	222.48	815.77	376	100	1.34	2.63
G3 Rereading Duration	292	NA	46.29	1099.32	169	109	3.23	19.50
G3 Saccade Amplitude	292	NA	1.26	6.24	2.47	0.62	1.45	4.90
G3 WJ Oral Comp SS	290	.76	71.00	136.00	113.24	12.03	−0.55	−0.12
G3 OWLS Listening Comp SS	290	.91	57.00	138.00	110.21	13.66	−1.02	1.36
G3 WJ Letter-Word ID SS	290	.91	59.00	135.00	105.69	11.67	−0.84	1.16
G3 WIAT Word Reading SS	290	.95	62.00	139.00	104.30	14.88	−0.35	−0.13
G3 Sight Word Efficiency SS	290	.93***	55.00	134.00	101.41	15.49	−0.35	−0.11
G3 WIAT Reading Comp SS	290	.79	49.00	143.00	105.71	14.78	−0.06	0.85
G3 WJ Passage Comp SS	290	.83	55.00	133.00	98.16	10.49	−0.44	1.34

Mean age = 6.36 [*SD* =.52] ranging from 6.01 years to 9.02[2] years in Grade 1; mean age = 8.79 [*SD* =.63] ranging from 8.04 years to 11.09 years in Grade 3). Reliability estimates were from the sample in this study. Unless otherwise noted, raw scores are reported. G1 = Grade 1; SS = standard score; RAN = rapid automatized naming; G3 = Grade 3; WJ = Woodcock-Johnson; Comp = comprehension; OWLS = Oral and Written Language Scales; ID = identification; WIAT = Wechsler Individual Achievement Test.

*Good et al., 2001; ** Wagner et al., 1999; ***Wagner et al., 2012

Apparatus and procedure

Eye movements were recorded using an EyeLink1000 desktop mounted system with a sampling rate of 500 Hz. Viewing and recording were binocular, but only data from the right eye were used for the current analyses. Reading materials were presented in black color on a gray background using Courier New font in 15-point size with double line spacing. On a 21-inch monitor with a screen resolution of 1024*768 this resulted in a letter size of .33 degree of visual angle. In order to allow for accurate vertical measurement, each passage was broken up into two to three paragraphs, each consisting of five to seven lines. Each paragraph was presented on a separate screen. Children were encouraged to move as little as possible during the measurement but were allowed to move around between passages. The camera was calibrated before each passage, using a 9-point calibration and validation routine. In addition, before each paragraph, an additional drift correction check was performed. Deviations larger than .5 degree of visual angle resulted in a new calibration.

Children were instructed to read the text in their normal reading speed so that they understood the content. To ensure that children read for meaning or comprehension, an easy literal comprehension question was asked after each passage and answers were recorded digitally. However, these data were not used in the analysis because the questions were very easy and were not meant to be a reliable indicator of children's comprehension skill.

Eye movement variables

For the current study, we focused on two temporal eye movement variables, gaze duration and rereading duration, and one spatial parameter, saccade amplitude. Gaze duration is the sum of all fixation durations on a word during first pass reading, whereas rereading duration is the sum of all subsequent fixation durations on a given word. Saccade amplitude measures the size of an eye movement between two fixations in letter units. For the current analyses, we used the length of the first incoming inter-word saccade for each word to calculate mean saccade amplitude.

Working memory and emergent literacy skills in Grade 1

Working memory

A widely used listening span task was used (e.g., Daneman & Merikle, 1996). After hearing sentences involving common knowledge (e.g., apples are blue), the child was asked to identify whether the heard sentences were correct or not (*yes/no* responses) and identify the last word in each of the sentences they heard in order. The child's responses about the veracity of the sentences were not scored, but his or her responses on the last words of the sentences were scored. Responses with the correct last words in correct order were given credit, whereas responses with incorrect words or incorrect order were scored zero. There were four practice items and 13 test items. The test discontinued after three consecutive incorrect responses.

Phonological awareness

The Elision subtest of the Comprehensive Test of Phonological Processing (CTOPP; Wagner, Torgesen, & Rashotte, 1999) was used. In this task, the child was asked to delete a given sound and say what was left (e.g., delete/k/from *cup*).

Orthographic awareness

To assess children's awareness of orthographic patterns and rules in English, a previously used experimental task was employed (Kim et al., 2013). In this task, the child was asked to look at a pair of pseudo words, where one of the two words violated English orthographic patterns (e.g., akke – noop), and to circle the word that "most looked like a real word." There was one practice item and 50 test items.

Morphological awareness

A previously used experimental task (Kim et al., 2013) was employed. In this task, the child heard a word (e.g., happy) followed by a sentence with a missing word (e.g., *When the student did not get an A, he was very* ________.) and was asked to complete the sentence with a related word. The items included inflectional morphemes and derivational words with suffixes (see Kim et al., 2013, for further details). There was one practice item and 40 test items.

Letter naming fluency

The letter naming fluency subtest of the Dynamic Indicators of Basic Early Literacy Skills (DIBELS; Good, Simmons, & Kame'enui, 2001) was used. The child was asked to name upper- and lower-case alphabet letters randomly arranged in 11 rows of 10 letters. The number of correctly identified letters in a minute was the score.

Rapid automatized naming

The Rapid Letter Naming subset of the CTOPP (Wagner et al., 1999) was used. The child was shown six letters that were randomly presented in a 9 by 4 matrix and was asked to name them. The time taken to read the letters in a minute was the score.

Reading and language skills in Grade 3

Reading comprehension

Two normed tasks were used: the Passage Comprehension subtest of the Woodcock-Johnson III (WJ; Woodcock, McGrew, & Mather, 2001) and Reading Comprehension subtest of the Wechsler Individual Achievement Test-III (WIAT; Wechsler, 2009). In the WJ Passage Comprehension test, the child was asked to read sentences and short passages and fill in blanks. In the WIAT Reading Comprehension subtest, the child was asked to read passages and answer multiple choice questions.

Word reading

Children's word reading skill was measured by the following three tasks: the Letter-Word Identification subtask of WJ, the Word Reading subtask of WIAT, and the Sight Word Efficiency subtask of the Test of Word Reading Efficiency-2 (TOWRE; Wagner, Torgesen, & Rashotte, 2012). These tasks required the child to read aloud isolated words of increasing difficulty. The first two tasks were untimed tasks (i.e., an accuracy measure), whereas Sight Word Efficiency was a timed task (45 s; i.e., an efficiency measure).

Listening comprehension

The Listening Comprehension Scale of the Oral and Written Language Scales-II (OWLS; Carrow-Woolfolk, 2011) and the WJ Oral Comprehension subtest (Woodcock et al., 2001) were used to measure children's listening comprehension. In the OWLS Listening Comprehension task, the child was asked to point to the picture that best describes the heard sentences and connected texts (e.g., short stories). In the WJ Oral Comprehension subtest, the child was asked to complete the heard sentences (e.g., People sit in _____.) and short paragraphs.

Procedures

Children were individually assessed in quiet spaces are participating schools in several sessions of 30 to 40 minutes per session (approximately two sessions in Grade 1; four sessions in Grade 3). Assessors were rigorously trained and had to meet 99% reliability in a fidelity check before they were allowed to work with children.

Data analytic strategies

Structural equation models were used to address the research questions. Latent variables were created for word reading, listening comprehension, and reading comprehension, which were each measured with multiple tasks. The first research question was addressed by including working memory and emergent literacy skills as predictors of the three eye movement variables (Figure 2). To address the second research question, gaze duration, rereading duration, and saccade amplitude were included as predictors of reading comprehension simultaneously (Figure 3). The third research question was addressed by fitting the model shown in Figure 4, which is aligned with Figure 1, where word reading and listening comprehension were predictors of eye movements and reading comprehension, and working memory and emergent literacy skills were predictors of word reading, listening comprehension, and eye movements. Note that for the relations of Grade 1 variables to Grade 3 listening comprehension in Figure 4 model, only the paths from Grade 1 working memory and morphological awareness were allowed in line with DIER (Kim, 2020a, 2020b). Also note that when the other paths (e.g., phonological awareness) were allowed, they were not statistically significant (not shown). The comparative fit and Tucker-Lewis indexes were used to evaluate the incremental fit of the model with

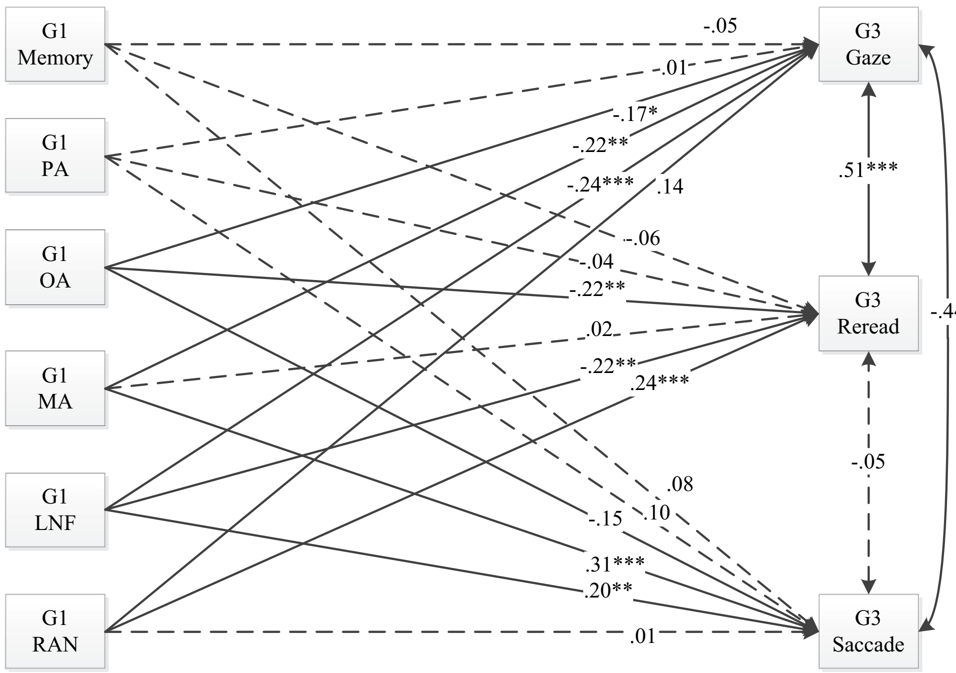

Figure 2. Structural relations between Grade 1 working memory and emergent literacy skills and Grade 3 eye movements (Research Question 1). Covariance between exogenous variables were allowed but are not shown here due to clutter. Standardized path coefficients are presented. Those with solid lines represent statistically significant relations and those with dashed lines represent statistically non-significant relations. G3 = Grade 3; Gaze = Gaze Duration; Reread = Rereading Duration; Saccade = Saccade Amplitude; G1 = Grade 1; PA = phonological awareness; OA = orthographic awareness; MA = morphological awareness; LNF = letter naming fluency; RAN = rapid automatized naming. Residual error covariances are automatically estimated in multiple, path analysis and are reported here. * *p* <.05. ** *p* <.01. *** *p* <.001.

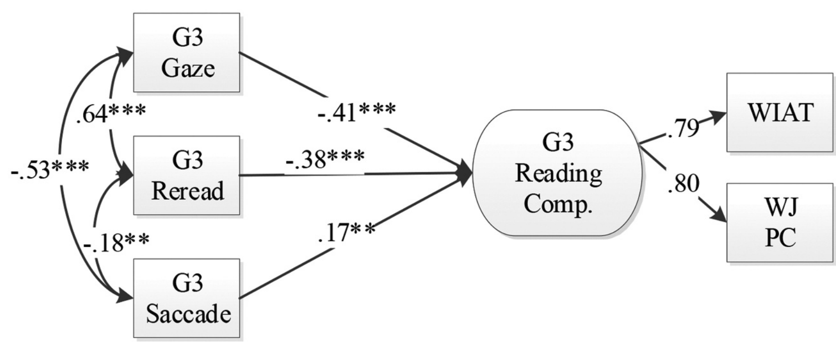

Figure 3. Structural relations between Grade 3 eye movements and Grade 3 reading comprehension (Research Question 2). Standardized path coefficients are presented. Those with solid lines represent statistically significant relations and those with dashed lines represent statistically non-significant relations. G3 = Grade 3; Comp. = Comprehension; WIAT = Wechsler Individual Achievement Test; WJ PC = Woodcock-Johnson Passage Comprehension; Gaze = Gaze Duration; Reread = Rereading Duration; Saccade = Saccade Amplitude.

values above .90 deemed as acceptable (Grimm & Ram, 2011). Additionally, the root-mean-square error of approximation was estimated along with its 90% confidence interval as well as standardized root mean squared residual (SRMR); point estimates less than .10 are considered acceptable (Grimm & Ram, 2011).

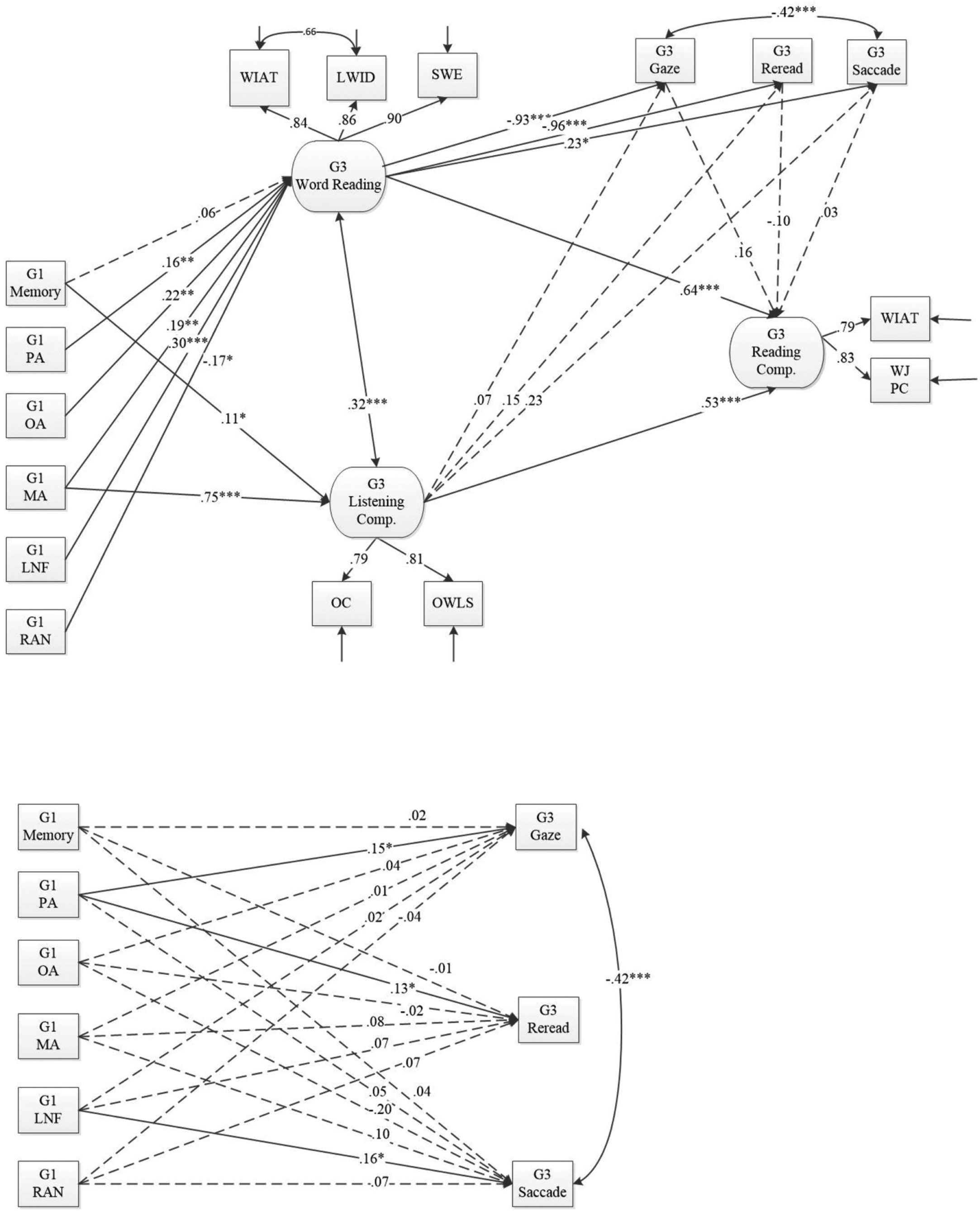

Figure 4. Structural relations among Grade 1 emergent literacy skills and Grade 3 word reading, listening comprehension, eye movements, and reading comprehension (Research Question 3). The relations were examined in a single model but the bottom portion of this figure breaks out the relations of Grade 1 emergent literacy skills to Grade 3 eye movements to facilitate visual inspection and reduce crowding in the main figure. Residual covariances between WIAT and LWID were allowed for method covariance as these two were untimed tasks whereas SWE was a timed task. The residual covariance between Gaze Duration and Saccade Amplitude was allowed for model fit, and it was the only statistically significant residual covariance among the endogenous variables, Graze Duration, Rereading Duration, and Saccade Amplitude. A full model where all covariances are allowed is available upon request. Standardized path coefficients are presented. Those with solid lines represent statistically significant relations and those with dashed lines represent statistically non-significant relations. G1 = Grade 1; PA = phonological awareness; OA = orthographic awareness; MA = morphological awareness; LNF = letter naming fluency; RAN = rapid automatized naming; WIAT = Wechsler Individual Achievement Test; LWID = Letter-Word Identification subtask of Woodcock-Johnson; SWE = Sight Word Efficiency subtask of the Test of Word Reading Efficiency; G3 = Grade 3; Comp. = comprehension; OC = Oral Comprehension subtest of Woodcock-Johnson; OWLS = Oral and Written Language Scales; WJ PC = Woodcock-Johnson Passage Comprehension. * $p < .05$. ** $p < .01$. *** $p < .001$.

Results

Descriptive statistics and preliminary analysis

Descriptive statistics are displayed in Table 1. In Grade 1, children's mean performances on normed tasks were in the average range. Grade 3 eye movement parameters showed an average of 376 ms (*SD* = 100) for gaze duration and 169 ms (*SD* = 109) for rereading duration, which are in line with previously reported values from third graders (Vorstius et al., 2014). However, average saccade amplitude in this study, which was around two and a half letters (*M* = 2.47, *SD* = 0.62), differed from average saccade amplitude reported by Vorstius et al. (2014). The difference may be due to reading format because Vorstius et al. used sentences, whereas the present study used paragraphs. Distributional properties were adequate for all variables with an exception of rereading duration, which had a kurtosis of 19.50.

Correlations (Table 2) of Grade 1 working memory and emergent literacy skills with Grade 3 language and reading skills ranged from weak to strong and were in expected directions (.12 to .66, including the negative relations for RAN). Working memory and emergent literacy skills were also weakly to moderately related with Grade 3 eye movement variables (.13 to −.42) such that working memory, phonological awareness, orthographic awareness, morphological awareness, and letter naming fluency were negatively related to gaze duration and rereading duration, whereas RAN had positive relations with them. An opposite pattern was found for the relations of working memory and emergent literacy skills with saccade amplitude. Gaze duration and rereading duration were negatively and moderately to strongly related to word reading and reading comprehension (−.52 to −.80) such that children with lower reading proficiency had longer gaze duration and rereading duration. Word reading and reading comprehension were positively and moderately related with saccade amplitude (.35 ≤ *r*s ≤ .39) such that those with more advanced reading proficiency had larger saccade amplitudes. Correlations were strong within each set of observed measures to be used in the latent variables: measures of word reading (.74 ≤ *r*s ≤ .90), listening comprehension (*r* = .62), and reading comprehension (*r* = .64).

Research Question 1: The Relations of Working Memory and Emergent Literacy Skills to Eye Movements

Figure 2 reports the standardized coefficients of working memory and emergent literacy skills in Grade 1 to the Grade 3 eye movement variables. No model fit information is available because the model was just-

Table 2. Correlations among manifest variables.

Variable	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1. G1 Working Memory	–														
2. G1 Phonological Awareness	.33	–													
3. G1 Orthographic Awareness	.26	.51	–												
4. G1 Morphological Awareness	.35	.51	.44	–											
5. G1 Letter Naming Fluency	.09+	.32	.28	.26	–										
6. G1 RAN	−.18	−.24	−.24	−.26	−.51	–									
7. G3 Gaze Duration	−.22	−.33	−.38	−.42	−.42	.37	–								
8. G3 Reread Duration	−.18	−.27	−.35	−.22	−.41	.41	.64	–							
9. G3 Saccade Amplitude	.21	.27	.13+	.38	.28	−.18	−.53	−.18	–						
10. G3 WJ Oral Comp	.29	.37	.34	.63	.16	−.22	−.37	−.21	.28	–					
11. G3 OWLS Listening Comp	.30	.40	.35	.66	.12+	−.20	−.42	−.25	.36	.62	–				
12. G3 WJ Letter-Word ID	.34	.57	.54	.55	.38	−.38	−.68	−.64	.38	.46	.52	–			
13. G3 WIAT Word Reading	.28	.55	.55	.49	.37	−.33	−.67	−.62	.38	.41	.45	.90	–		
14. G3 Sight Word Efficiency	.21	.39	.41	.37	.55	−.47	−.80	−.73	.37	.29	.34	.76	.74	–	
15. G3 WIAT Reading Comp	.31	.43	.34	.57	.37	−.38	−.58	−.52	.39	.53	.58	.68	.63	.59	–
16. G3 WJ Passage Comp	.35	.48	.47	.57	.35	−.31	−.60	−.56	.35	.60	.54	.74	.74	.62	.64

G1 = Grade 1; RAN = rapid automatized naming; G3 = Grade 3; WJ = Woodcock-Johnson; Comp = comprehension; OWLS = Oral and Written Language Scales; ID = identification; WIAT = Wechsler Individual Achievement Test. All correlations are statistically significant at $p < .01$ except those flagged by + ($p > .05$).

identified or saturated (see Appendix). Grade 1 orthographic awareness ($\gamma = -.17, p < .001$), morphological awareness ($\gamma = -.22, p < .001$), letter naming fluency ($\gamma = -.24, p < .001$), and RAN ($\gamma = .14, p < .001$) were significant predictors of gaze duration such that children with lower orthographic awareness, morphological awareness, and letter naming fluency, and those who took longer time in RAN had longer gaze duration. Orthographic awareness ($\gamma = -.22, p < .001$), letter naming fluency ($\gamma = -.22, p < .001$), and RAN ($\gamma = .24, p < .001$) all uniquely predicted rereading duration. Finally, morphological awareness ($\gamma = .31, p < .001$) and letter naming fluency ($\gamma = .20, p < .01$) both uniquely and positively predicted saccade amplitude whereas orthographic awareness had a suppression effect on it ($\gamma = -.15, p < .05$).

To summarize, orthographic awareness and letter naming fluency were related to all the eye movement variables (albeit a suppression effect of orthographic awareness on saccade amplitude); morphological awareness was independently related to gaze duration and saccade amplitude; and RAN was independently related to gaze duration and rereading duration. Working memory and phonological awareness were not independently related to any of the eye movement variables after accounting for the other variables in the model. The amount of variance explained by working memory and emergent literacy skills was 32% in gaze duration, 29% in rereading duration, and 19% in saccade amplitude.

Research Question 2: The Relations of Eye Movements to Reading Comprehension

The structural equation model of eye movements to reading comprehension resulted in excellent fit to the data, $\chi^2(2) = 1.46$, $p > .500$, CFI = 1.00, TLI = 1.00, RMSEA = .000 [90% CI = .00, .11], SRMR = .009. Results in Figure 3 showed moderate and negative relations of gaze duration ($\gamma = -.41, p < .001$) and rereading duration ($\gamma = -.38, p < .001$), and a weak and positive relation of saccade amplitude ($\gamma = .17, p < .01$) to reading comprehension after controlling for each other. The common and unique variance across the eye movement indicators explained 63% of the variance in reading comprehension.

Research Question 3: The Relations among Working Memory and Emergent Literacy Skills, Word Reading, Listening Comprehension, Eye Movements, and Reading Comprehension

The structural equation model shown in Figure 4 had acceptable fit to the data, $\chi^2(57) = 196.76$, $p < .001$, CFI = .95, TLI = .90, RMSEA = .092 [90% CI = .078, .106], SRMR = .04. Standardized coefficients are displayed in Figure 4.

The relations of working memory and emergent literacy skills to word reading and listening comprehension

All the emergent literacy skills significantly predicted word reading with coefficients ranging from $\gamma = -.17$ for RAN ($p < .05$) to $\gamma = .30$ for letter naming fluency ($p < .001$), resulting in 55% of the variance in word reading being explained. Working memory was not related to word reading after controlling for the emergent literacy skills ($\gamma = .06, p = .26$). Working memory ($\gamma = .11, p = .04$) was weakly and morphological awareness ($\gamma = .75, p < .001$) was strongly related to listening comprehension. A total of 64% of the variance in listening comprehension was explained.

The relations of working memory, emergent literacy skills, and word reading to eye movements

Working memory and the vast majority of emergent literacy skills were not related to eye movements after accounting for their relations to word reading and listening comprehension (see the bottom panel of Figure 4). An exception was letter naming fluency, which was weakly and positively related to saccade amplitude ($\gamma = .16, p = .03$) after accounting for the other emergent literacy skills as well as word reading and listening comprehension. Phonological awareness had a suppressor effect on gaze duration ($\gamma = .15, p = .02$; it was negatively related in the bivariate correlation [–.33] in Table 2, but positively related in the structural equation model in Figure 4) and rereading duration ($\gamma = .13, p = .04$).

Word reading was strongly and negatively related to gaze duration (β = − .93, $p < .001$) and rereading duration (β = − .96, $p < .001$), and also to saccade amplitude (β = .23, $p = .03$). In contrast, listening comprehension was not related to any of the eye movement variables ($ps \geq .40$) after controlling for word reading and the other variables in the model. The total amount of variance explained was as follows: 73% in gaze duration, 66% in rereading duration, and 26% in saccade amplitude.

The relations of eye movements to reading comprehension

After controlling for word reading and listening comprehension, and Grade 1 working memory and emergent literacy skills, eye movements were not significantly related to reading comprehension ($ps \geq .08$). Both word reading (β = .64, $p < .001$) and listening comprehension (β = .53, $p < .001$) were uniquely related to reading comprehension, with the total effects explaining 99.9% of its variance.

Discussion

Reading involves a complex array of processes, and these processes draw on skills. In the present study, we simultaneously investigated the relations among reading processes (measured by eye movements), reading skills (word reading and reading comprehension), and predictors of reading skills (working memory, emergent literacy, and listening comprehension).

With regard to the relations of working memory and emergent literacy skills to eye movements, several findings are noteworthy and extend previous studies. A novel aspect of this study was the inclusion of a comprehensive set of emergent literacy skills. Extending previous work on the role of RAN in eye movements for children with dyslexia (Pan et al., 2013; Yan et al., 2013), we found the relation of RAN to gaze duration and rereading duration even after accounting for the other emergent literacy skills such that faster RAN was associated with shorter gaze duration and rereading duration. The present findings also highlight the unique relations of the other emergent literacy skills to eye movements. When examined separately in bivariate correlations, phonological awareness, orthographic awareness, morphological awareness, and letter naming fluency were all negatively related to gaze duration and rereading duration, indicating that advanced proficiency in these emergent literacy skills is associated with shorter gaze duration and rereading duration (Table 2). However, when emergent literacy skills were examined all together as predictors of eye movements, results varied somewhat for different eye movement outcomes. For gaze duration, orthographic awareness, morphological awareness, and letter naming fluency remained statistically significant; a similar pattern was found for rereading duration with an exception of morphological awareness. The unique relation of morphological awareness to gaze duration appears to be in line with the hypothesis that gaze duration involves initial semantic processing (Inhoff & Radach, 1998; Rayner, 1998). Taken together, for both gaze duration and rereading duration, important unique factors include children's skill to recognize legal orthographic patterns in English, their efficiency and automaticity in letter naming, and RAN.

For saccade amplitude, morphological awareness and letter naming fluency were uniquely and positively related. Higher morphological awareness might reduce the need to fixate on certain prefixes or suffixes, resulting in overall longer saccade amplitudes. Interestingly, letter naming fluency was uniquely related to saccade amplitude, even after accounting for word reading and listening comprehension (see Figure 3). The independent contribution of letter naming fluency to saccade amplitude may be explained by parafoveal preview. If letters can be recognized rapidly, more resources are available for parafoveal preview and therefore, more information from the next word can be preprocessed within the ongoing fixation, allowing a longer saccade to be programmed (Haikio, Bertram, & Hyona, 2010; Rayner, 1986). This result suggests the importance of automatic and rapid retrieval of meaning in reading (Perfetti, 2007) and that the perceptual span and use of parafoveal information contributes to successful reading over and above word reading. Studies have shown that the efficient use of parafoveal information presupposes that basic processes of reading have been mastered

(Sperlich et al., 2016, 2015). Thus, children's skill to recognize and retrieve letters with automaticity would influence the size of their saccades when reading connected text for comprehension. Interestingly, phonological awareness was not uniquely related to saccade amplitude or the other eye movements after controlling for the other emergent literacy skills, and this appears to be due to large shared variance with orthographic awareness and morphological awareness (see Table 2).

We also found that the relations of emergent literacy skills to eye movements are mostly mediated by word reading skill, a similar finding to that of Kuperman and Van Dyke's (2011) study with adolescents and adults. As shown in Figure 4, emergent literacy skills were related to word reading, and once word reading and listening comprehension were accounted for, emergent literacy skills were not related to eye movements, indicating that their relations are indirect via word reading. Overall these results are in line with computational reading models (E-Z reader, Glenmore, and SWIFT), which hypothesize word reading and associated orthographic, phonological, and semantic processes as the primary cause for oculomotor-visual processing in reading.

The present findings also revealed the nature of the relation of working memory and eye movements. Working memory was related to the three eye movement variables (Table 2), which is in line with previous studies with adults (Kuperman & Van Dyke, 2011; Traxler et al., 2012). However, once emergent literacy skills were accounted for, working memory was not uniquely related to eye movement variables, indicating that its contribution to eye movements is largely shared with those of emergent literacy skills, given the relation of working memory to emergent literacy skills (Biname & Poncelet, 2015; Deacon et al., 2009; Kim, Cho, & Park, 2018). It should be noted that these results do not deny the role of working memory in eye movements, but instead suggest that its role is primarily indirect via emergent literacy skills.

Not surprisingly, eye movements were related to reading comprehension – the three eye movement variables explained 63% of the variance in reading comprehension. Specifically, the relations were moderate to strong in bivariate correlations (Table 2), and weak to moderate after accounting for each other (Figure 2) such that longer gaze duration and longer rereading duration were associated with lower performance on reading comprehension whereas longer saccade amplitude was positively related to reading comprehension. Also not surprising were the relations of word reading and listening comprehension to reading comprehension, which are in line with many previous studies (e.g., Florit & Cain, 2011; Hoover & Gough, 1990; Kim, 2017, 2020b; Tunmer & Chapman, 2012). When word reading and listening comprehension as well as working memory and emergent literacy skills were controlled for, however, eye movement variables were no longer uniquely related to reading comprehension. These results appear to be due to the large overlap or shared variance between word reading and eye movements, gaze duration, and rereading duration in particular. Word reading was very strongly and negatively related to gaze duration and rereading duration (Figure 4), which is convergent with our hypothesis and previous studies (e.g., Connor et al., 2014; Kim et al., 2019; Kim, Vorstius, & Radach, 2018). These results are also in line with the E-Z reader model, which hypothesizes word reading as the "engine" that drives eye movements in reading (Reichle, Rayner, & Pollatsek, 2006), and the SWIFT model, which considers word reading as the primary constraint for the visuo-oculomotor processes (Engbert et al., 2002). Taken together, these results indicate that individual differences in online processes measured by eye movements predict reading comprehension, but their effects on reading comprehension are largely shared with that of word reading and listening comprehension skills at least for developing readers in Grade 3.

Our hypothesis about the relation of listening comprehension to eye movements was only partially supported. Because listening comprehension captures linguistic and cognitive processes (Kendeou et al., 2008; Kim, 2016, 2017; Tompkins et al., 2013), listening comprehension was hypothesized to relate to gaze duration and rereading duration. Listening comprehension was weakly to moderately related to these eye movements in bivariate correlations ($-.21 \le rs \le -.42$; Table 2). Once word reading was taken into consideration, however, listening comprehension was not independently related to eye movements (Figure 4). One explanation for this includes the developmental phase of reading for the sample children – listening comprehension is not related to eye movements due to the large constraining role of word reading for developing readers, at least for the present sample in Grade 3 (as shown in the very strong relations of word reading to eye movements). If this explanation is correct, a reasonable corollary is that as the constraining role of word reading decreases with development of word reading skills, listening comprehension may be uniquely related to eye movements over and above word reading. Future studies are warranted.

Limitations and conclusion

The present findings reflect those for developing readers in Grade 3 learning to read in English. Therefore, replications and extensions with children at different phases of reading development (e.g., more advanced stages such as upper elementary grades) and from different linguistic and orthographic backgrounds (see Seymour, Aro, & Erskine, 2003; Share, 2008) are needed to further illuminate the relations between individual characteristics and eye movements. One way to replicate the current work is using a design where students' reading comprehension is based on the same tasks/passages for eye-tracking. We chose to use different tasks for eye tracking versus reading comprehension measurement in the present study because eye-tracking with normed reading comprehension tasks does not allow us to use norm information as eye tracking is not aligned with assessment protocol. Future work can address this by employing several normed reading comprehension tasks where one of them is used for eye tracking. It should be also noted that reliability estimate of the working memory task was less than ideal, and therefore, results should be interpreted with caution, and future replication is necessary.

Several other aspects of the present study would benefit from more detailed examination in future studies. The statistical models examined in this study were informed by theory and prior evidence. However, alternative structural relations are certainly possible and should be investigated in future studies. For example, it is theoretically plausible that gaze duration predicts rereading duration (in Figures 2-4), but in this study, we allowed covariance between them as this was beyond the scope of the present study (see MacCallum, Wegener, Uchino, & Fabrigar, 1993 for a discussion of equivalent statistical models). In addition, nesting of children in classrooms and schools were not accounted for in statistical modeling and a future study addressing this aspect is needed.

Another example is our finding that both RAN and letter naming fluency are independently related to gaze duration and rereading duration after accounting for the other emergent literacy skills and working memory (Figure 2b). Previous investigations with developing readers focused on RAN, and the relation of RAN to eye movements has been explained by perceptual span (i.e., less automatized translation of visual symbols to phonological output is expected to reduce a perceptual span; see Pan et al., 2013; Yan et al., 2013). If this is indeed the case, then RAN's relation to eye movements would be largely shared with that of letter naming fluency. On the contrary, we found that letter naming fluency makes an additional contribution to gaze duration and rereading duration over and above RAN as well as the other emergent literacy skills. Letter naming fluency captures one's automaticity and efficiency in recognizing alphabet letters and retrieving their names, and has been shown to be a strong predictor of word reading (Hecht, Burgess, Torgesen, Wagner, & Rashotte, 2000; Ritchey & Speece, 2006). RAN is also a consistent predictor of word reading, but its nature has been debated in the literature (Georgiou, Parrila, Cui, & Papadopoulos, 2013; Schatschneider, Carlson, Francis, Foorman, & Fletcher, 2002). Future studies should explore similarities and differences in what RAN and letter naming fluency capture, and their unique relations to reading skills and reading processes.

The present study was an effort to expand our knowledge about the relations of individual differences in reading and reading-related skills to online reading processes measured by eye movements. Our findings revealed several novel findings, including the relations of emergent literacy skills to eye movements; a mediating role of word reading in the relation of emergent literacy skills to eye movements; and the nature of relations among word reading, eye movements, and reading comprehension. These findings underscore a need for future investigations on the relations of reading skills and processes simultaneously.

Notes

1. This was due to unavailability of students in one school.
2. One child was held back and thus, substantially older than the rest.

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Disclosure statement

The authors declare that there is no conflict of interest.

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Appendix

Discussion on just-identified or saturated model can be found in the literature (e.g., Hershberger & Marcoulides, 2013; Raykov, Marcoulides, & Patelis, 2013). A just-identified model may serve as a benchmark by which other models with positive degrees of freedom may be compared. The just-identified model is also useful in circumstances where the model parameters and standard errors are of interest, and where, "no existing theory or a priori hypothesis can be used to develop further parameter constraints rendering a model under consideration with positive degrees of freedom" (Raykov, Lee, Marcoulides, & Chang, 2013, p. 1055). Our use of the saturated model in Figure 2 is part of a broader model-building framework to situate the findings in context of the models presented in Figures 3 and 4. It can be noted that the models specified in Figure 2 would be structurally equivalent to running three, separate multiple regression models.