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An Analysis of Reading Skill Development using E-Z Reader

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Abstract

Previously reported simulations using the E-Z Reader model of eye-movement control suggest that the patterns of eye movements observed with children versus adult readers reflect differences in lexical processing proficiency (Reichle et al., 2013). However, these simulations fail to specify precisely what aspect(s) of lexical processing (e.g., orthographic processing) account for the concurrent changes in eye movements and reading skill. To examine this issue, the E-Z Reader model was first used to simulate the aggregate eye-movement data from 15 adults and 75 children to replicate the finding that gross differences in reading skill can be accounted for by differences in lexical processing proficiency. The model was then used to simulate the eye-movement data of individual children so that the best-fitting lexical-processing parameters could be correlated to measures of orthographic knowledge, phonological-processing skill, sentence comprehension, and general intelligence. These analyses suggest that orthographic knowledge accounts for variance in the eye-movement measures that is observed with between-individual differences in reading skill. The theoretical implications of this conclusion will be discussed in relation to computational models of reading and our understanding of reading skill development.

Keywords

development; eye movements; E-Z Reader; lexical processing; reading; skill

One of the most important pedagogical questions is: What allows a beginning reader to become a skilled reader? The purpose of this paper will be to examine this question in more detail, using a computational model of eye-movement control in reading, *E-Z Reader* (Reichle, 2011), to simulate and interpret data from an eye-movement experiment involving both skilled adult readers and beginning (children) readers of varying ability. More

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specifically, the theoretical assumptions of the model will be used as mediating variables to examine possible relationships among three important predictors of reading ability (i.e., orthographic knowledge, phonological-processing skill, and sentence comprehension) and various eye-movement measures of reading fluency (e.g., fixation durations). By doing this, our goal will be to more fully specify why the eye movements of beginning readers are different from those of skilled readers, and in so doing, possibly provide further insight into the cognitive processes that are important in learning how to read.

A considerable amount has been learned about the mental processes that support skilled (adult) reading using eye movements (for reviews, see Rayner, 1998, 2009). More recently, the development of eye trackers that are easier to use and hence more amenable to being used with young children has allowed reading researchers to study the eye movements of children who are just beginning to read (for a review, see Blythe & Joseph, 2011). This work has revealed a number of important facts about the pattern of similarities and differences in the eye movements of children versus adults. For example, relative to the latter group, children tend to make shorter saccades and longer fixations, with more frequent regressions back to earlier parts of the text, resulting in a slower overall reading rate (Buswell, 1922; Rayner, 1986; Taylor, 1965). Moreover, although children tend to direct their saccades in a manner similar to adults, thus resulting in similar fixation landing-site distributions, children are more likely to initiate a refixation following fixations near the end of words (Vitu, McConkie, Kerr, & O'Regan, 2001; Joseph, Liversedge, Blythe, White, & Rayner, 2009). This is likely due to the fact that children are slower than adults at processing words, as suggested by the observation that children's fixation durations are more modulated by word frequency, resulting in more pronounced *word-frequency effects* (Blythe, Liversedge, Joseph, White, & Rayner, 2009; Hyönä & Olson, 1995; Joseph, Nation, & Liversedge, 2013). This tendency to process words more slowly and refixate more often also results in more pronounced *inverted optimal-viewing positions (IOVP) effects*, or the finding that initial fixations tend to be longer in duration near the center of words than at their edges (Aghababian & Nazir, 2000; Vitu, Lancelin, & d'Unienville, 2007; Vitu et al., 2001). Finally, children also have a smaller perceptual span, or "region from which useful information can be obtained during a fixation in reading" (Rayner, 1986, p. 212; see also Häikiö, Hyönä, & Bertram, 2010; Häikiö, Bertram, Hyönä, & Niemi, 2009). The precise reason for this last finding remains unclear. For example, slower lexical processing may reduce the parafoveal preview of upcoming words, thereby reducing the perceptual span (Reichle et al., 2013). Or alternatively, a smaller visual-attention span (i.e., the number of distinct visual elements that can be accurately identified in parallel; Bosse & Valdois, 2009; Lobier, Dubois, & Valdois, 2013) may reduce the rate of word processing. For example, Prado, Dubois, and Valdois (2007) showed that French children having smaller visual-attention span made more first-pass fixations during text reading than children of the same age having a larger visual-attention span.

These similarities and differences obviously provide hints about how the cognitive processes underlying reading change as beginning readers become more proficient. The challenge is to therefore explain these patterns of findings so as to better understand what those cognitive processes are and how they change with reading expertise. Reichle et al. (2013) recently provided one such account. This was done by first using the E-Z Reader model (Reichle,

2011) to explore the possible ways that one might account for the observed differences between the eye movements of children versus adults. More specifically, across a series of simulations, the values of the parameters that control various components of the model (e.g., the rate of lexical processing) were varied to determine whether those parameters could mediate the patterns of eye movements observed in beginning readers. Because the model's default parameter values had been selected to fit the eye-movement data from skilled adult readers (from an experiment reported by Schilling, Rayner, & Chumbley, 1998), these values provided a baseline for examining how changing the parameters affected the model's performance. By systematically varying the values of the parameters that control both language processing and saccadic programming and execution, Reichle et al. demonstrated that changing the value of the parameter that controls the overall rate of lexical processing (thereby slowing its rate of completion) was sufficient for the model to (qualitatively) simulate the patterns of eye movements of children. This demonstration suggests that the rate of lexical processing may be responsible for the differences between eye movements of children and adults, which in turn suggests that word identification is the primary determinant of reading skill.

The hypothesis that lexical processing proficiency mediates reading skill is consistent with both prior conjectures and evidence related to reading skill differences. For example, Perfetti's *lexical-quality hypothesis* (2007; see also Perfetti, & Stafura, 2014) stipulates that the quality of one's lexical representations and hence the ease of accessing orthographic, phonological, and semantic information from printed text is one of the key factors determining reading skill. In the same line, the experiment reported by Schilling et al. (1998) examined individual differences in word-identification skill by having subjects perform three different tasks on a set of high- and low-frequency target words: (1) *lexical decision*, or rapidly discriminating target words from pseudo-words; (2) *naming*, or rapidly pronouncing the target words; and (3) natural reading of sentences containing the target words. The word-frequency effect was found in all three tasks, with shorter response latencies for high- than low-frequency words in both lexical decision and naming, and shorter fixation durations on high- than low-frequency words. More importantly, the overall response latencies were correlated across subjects; subjects having shorter fixation durations also showed faster lexical-decision and naming responses. This latter result is consistent with the hypothesis that lexical processing proficiency (as measured by lexical decision and naming) mediates reading skill (as measured by eye movements).

Finally, it is important to note that several computational models have been developed which provide formal descriptions of the processes that are involved in the identification of printed words (e.g., Ans, Carbonnel & Valdois, 1998; Coltheart, Rastle, Perry, Ziegler & Langdon, 2001; Perry, Ziegler & Zorzi, 2007; Seidenberg & McClelland, 1989; for a review, see Reichle, 2015). The majority of these models assume the existence of two distinct reading procedures—a global procedure based on parallel processing and word-specific knowledge, and an analytic procedure based on serial processing and sub-lexical knowledge of grapheme-to-phoneme correspondences. In order to better understand how the E-Z Reader parameters might be related to these two types of reading procedures, the children who participated in our study were administered a battery of psychometric tests that measured

either word-specific orthographic knowledge or sub-lexical phonological processing abilities.

Our two tests of word-specific orthographic knowledge included: (1) the spelling of inconsistent words (e.g., write *island* under dictation); and (2) orthographic lexical decision (e.g., identify the real word in the set: *rane*, *rain*, and *rayn*). The spelling of inconsistent words requires the retrieval of the specific orthographic form of the dictated word from long-term memory because the application of grapheme-phoneme mappings would result in inaccurate spellings (e.g., writing “iland” in response to *island*). Similarly, the orthographic lexical decision task requires the retrieval of a word’s correct orthographic form so that that form can be discriminated from two other orthographic forms that are also consistent with the word’s pronunciation. Accordingly, accurate spelling of inconsistent words is typically interpreted as evidence of good orthographic learning (Share, 1995, 1999, 2004). And in the same way, the orthographic lexical decision task has been widely used as a measure of orthographic knowledge. For example, the task predicts variance in word identification after phonological-processing skill has been controlled (Barker, Torgesen, & Wagner, 1992; Cunningham & Stanovitch, 1990; McBride-Chang, Manis, Seidenberg, Custodio, & Doi, 1993). As Olson, Kliegl, Davidson, and Foltz (1995, p. 165) indicated: “a partially independent measure of orthographic knowledge can be obtained by requiring subjects to select the correct spelling of a word among homophones.”

Our two tests of sub-lexical phonological processing skill included: (1) pseudo-word spelling (e.g., write *pilshen* under dictation); and (2) pseudo-word homophony judgments (e.g., identify the non-homophonic string in the set: *plage*, *pleige*, and *plege*). Because pseudo-words are not represented holistically in long-term memory, their spelling under dictation by definition must instead be based on general knowledge of the statistical regularities of grapheme-to-phoneme correspondences. And for exactly the same reason, knowledge of grapheme-to-phoneme correspondences is also necessary to generate the pronunciations of pairs of pseudo-words in order to decide whether or not they are homophones. Although pseudo-word spelling has not (as far as we know) been widely used as a measure of phonological-processing skill, the pseudo-word homophony judgment task has. For example, Peterson, Pennington, and Olson (2013) demonstrated that the task predicts reading performance of children with phonological dyslexia (which is typically associated with poor pseudo-word reading).

Finally, it is important to note that comparisons of dyslexic and normal readers also provides converging evidence demonstrating the partial independence of orthographic and phonological knowledge using tasks similar to ours. Indeed, tasks such as ours have been used to identify subsets of dyslexic readers that exhibit dissociations between their orthographic and phonological knowledge, with some showing poor orthographic knowledge but normal phonological processing (Brown & Doctor, 1995; Brunsdon, Coltheart, & Nickels, 2005; Castles & Coltheart, 1996; Dubois, Kyllingsbaek, Prado, Musca, & Peiffer, 2010; Hanley & Gard, 1995; Sprenger-Charolles Colé, Lacert, & Serniclaes, 2000; Temple & Marshall, 1983; Valdois Bosse, Ans, Carbonnel, & Zorman, 2003) and others showing the exact opposite pattern (Campbell & Butterworth, 1985; Howard & Best, 1996; Snowling & Hulme, 1989; Valdois et al., 2003; Zoubrinetzky, Bielle, & Valdois, 2014). Interestingly,

genetic studies have also indicated that orthographic and phonological skills are differently sensitive to genetic influence (e.g., Olson, Wise, Conners, Rack & Fulker, 1989).

Based on these findings, then, the current paper explores more deeply whether differences in lexical processing might be causally related to differences in eye-movement patterns and reading skills (e.g., as measured by reading rate). First, we report the results of a new eye-movement experiment in which skilled adults and children of varied reading ability read the same short passage of text. Then, we report the results of new simulations using E-Z Reader to examine not only the differences between adults and children, but also the sources of variability among children. As will become apparent, the results of these simulations suggest that proficiency of orthographic processing mediates between-individual differences in eye movements, with children who are more proficient at orthographic processing exhibiting patterns of eye movements that are more indicative of skilled readers.

Experiment

Method

Participants—15 adults (23–29 years) and 106 children (10–13 years; $M = 11$ years) took part in the experiment. All of the adults were native or fluent French speakers and all children were native French speakers (4 were bilingual). The adults and the children's parents gave informed written consent prior to the study. All participants were naïve regarding the purpose of the study and were unpaid volunteers. The children were selected from an initial larger pool of children assessed with different language proficiency and reading tests. Pre-screening was conducted to ensure that all of the children attended school regularly and had normal or corrected-to-normal vision.

Apparatus—The passage of text that was used in the experiment was displayed on a 17-in. Dell 1704 monitor attached to a Dell Latitude E6530 computer interfaced with an SR Research EyeLink 1000 eye-tracking system having high spatial ($< 0.3^\circ$ of visual angle) and temporal (1,000 Hz) resolution. Viewing was binocular and both eyes were tracked as permitted by the quality of the calibration for both eyes. However, the eye-movement analyses reported below were completed using only data from the eye having the better calibration. The text was divided into two paragraphs, each containing 14 lines that were display in white mono-spaced font on a gray background. Participants were seated approximately 51 cm from the monitor so that three characters equaled approximately 1° of visual angle. The experiment was implemented and run using SoftEye software (Ionescu, Guyader, & Guerin-Dugué, 2009).

Materials—The text was a short narrative written in French and containing 212 words that was designed to be age-appropriate for 10–12 year-old children. The 12 3-alternative multiple-choice comprehension questions were designed to measure the participants' understanding of the specific text used in our study and to insure compliance with task demands. Also, prior to participating in the eye-movement experiment, the children also completed four psychometric tests (developed “in house”)¹ to evaluate orthographic knowledge and phonological-processing skill, as well as standardized measures of both

sentence comprehension and general intelligence. More specifically, the tests and what they measure are as follows:

- i. *inconsistent word spelling*: Each child was instructed to complete a written sentence by spelling a missing word that was orally pronounced by the examiner. Each of the 37 spelled words included at least one grapheme that could not be inferred from the application of common phoneme-grapheme mapping rules. Accurate performance thus required the retrieval of the orthographic form of the dictated words from memory, providing an estimate of word-specific orthographic knowledge.
- ii. *orthographic lexical decision*: Each child viewed 42 homophonic letter string triples (e.g., *dépar*, *départ*, and *dépard*) and indicate the correctly spelled French word (i.e., *départ*). All of the letter strings were orthographically legal and comprised of syllables found in other French words, so accurate performance required the retrieval of a word's orthographic form, thus providing a second estimate of word-specific orthographic knowledge.
- iii. *pseudo-word spelling*: Each child was instructed to spell 20 pseudo-words under dictation. Accurate performance necessitated parsing the spoken pseudo-words into their phonemes and then using general knowledge about grapheme-phoneme correspondences to spell the pseudo-words; as such, the task measures phonological processing rather than word-specific orthographic knowledge.
- iv. *homophony judgment*: Each child viewed 21 visually similar pseudo-word triples, two of which were homophones (e.g., *gentin*, /zâtê/; *jantin*, /zâtê/; and *gantîn*, /gâtê/), and instructed to indicate the non-homophonic item (i.e., *gantîn*). Accurate performance requires the use of grapheme-to-phoneme correspondences and thus provides a second measure of phonological-processing skill.
- v. *sentence comprehension* (*TeCoPé*; Ecalle et al., 2013): Each child was instructed to decide whether each pair of 24 written sentences had the same meaning or not. Accurate performance requires whatever semantic and syntactic processing is necessary to understand and compare the meanings of the sentences, thus measuring sentence comprehension rather than, for example, either orthographic or phonological knowledge, or general intelligence.
- vi. *general intelligence* (*Raven Progressive Matrices*; Raven, Court & Raven, 1998). Each child was instructed to indicate which of 6 possible missing elements best completed a visual pattern. The test consists of 5 sets containing 12 visual patterns each, with the patterns becoming increasingly difficult within each set. The test measures nonverbal reasoning ability and provide an estimate of general intelligence.

Procedure—Participants were instructed to read the passage of text silently for comprehension and to answer the 12 comprehension questions that were displayed after the

¹These tests were developed as part of the Ortholearn project, which was funded by the French Research National Agency (ANR-12-BSHS2-0013); for more information about the tests, contact Sylviane Valdois (sylviane.valdois@upmf-grenoble.fr).

passage. The participants were seated in a chair and a chin rest was used to restrict their head motion. The eye-tracker was then calibrated by instructing the participants to track a white dot displayed at 9 different screen locations. (As indicated, the eye-tracker was calibrated for both eyes.) The mean calibration error for the best calibrated eye was 0.55° ($SD = 0.16$; max. = 1.06) and 0.67° ($SD = 0.24$; max. = 1.85) for adults and children, respectively. After calibration, a fixation cross was displayed at the center of the screen until the computer detected the participant's gaze located within a rectangular area circumscribing the cross. The passage of text was then displayed until the participants pressed a button to answer the questions, each of which was then displayed one at a time below the text (which remained visible) until it was answered. The entire experiment lasted (on average) approximately 15 minutes for adults and 20 minutes for children.

Data Analysis—The data from 31 of our children were excluded from our analyses due to poor eye-tracker calibration and/or failure of our fixation-alignment software. And as will be discussed below, the data from 21 children were excluded because the best-fitting values of the E-Z Reader parameters were not reliable. Because of these exclusions, Table 1 shows the mean raw psychometric test scores for the two sub-samples excluded from our final analyses (i.e., $N = 31$ and $N = 21$) and the sub-sample (i.e., $N = 54$) of children included in final our analyses, along with the standard deviation of those scores, the maximum possible scores, and both the maximum and minimum observed scores. As the table shows, the scores span the full range of possible values. To determine if the mean scores differed across the sub-samples, we performed six ANOVAs using sub-sample as a one-way between-groups factor. These analyses indicated no significant group differences for inconsistent word spelling [$F(2, 105) = 0.42, p > 0.6$], orthographic lexical decision [$F(2, 105) = 0.03, p > 0.9$], or homophony judgment [$F(2, 105) = 0.83, p > 0.4$], but marginally significant group differences for pseudo-word spelling [$F(2, 105) = 2.93, p = 0.057$] and sentence comprehension [$F(2, 105) = 2.48, p = 0.08$] and a significant group difference for general intelligence [$F(2, 105) = 5.28, p < 0.01$]. However, because neither the orthographic or phonological test scores significantly differed across the different sub-samples, we verified the internal consistency of those four tests by calculating Cronbach's (1951) α coefficient using the $N = 106$ children in our samples. These analyses indicated that inconsistent word spelling ($\alpha = 0.74$), orthographic lexical decision ($\alpha = 0.71$), and homophony judgment ($\alpha = 0.72$) have good internal consistency, but that pseudo-word spelling ($\alpha = 0.54$) has acceptable/poor internal consistency.

Finally, we examined the relationships among the psychometric texts excluding only those children who provided no eye-movement data (e.g., due to poor calibration). Table 2 therefore shows the inter-correlations among these psychometric test scores using the remaining $N = 75$ children (after converting the raw scores to proportions correct). As the table shows, the tests are inter-correlated with each other. Because the orthographic and phonological test scores are correlated, one might argue that the two types of measures should be collapsed into a single variable representing lexical knowledge or processing skill. To determine whether this is appropriate, we performed a one-factor factorial analysis to test whether a single latent factor could explain both types of measures. Although the resulting χ^2 statistic ($\chi^2 = 3.0081, p = 0.22$) was not sufficient to reject the hypothesis that a single

(lexical) factor can explain the data, the residual variances were not homogeneous. Our analysis indicated less residual variance for the two orthographic tests (i.e., $\varepsilon_{\text{inconsistent word spelling}} = 0.2293$ and $\varepsilon_{\text{orthographic lexical decision}} = 0.3469$) than for the two phonological tests (i.e., $\varepsilon_{\text{pseudo word spelling}} = 0.7137$ and $\varepsilon_{\text{hymophony judgment}} = 0.6126$). For that reason, and because of the prior evidence that these tasks do measure separate types of lexical knowledge, the orthographic and phonological variables are considered separately in the remainder of this article. And because both orthographic knowledge and phonological-processing skill were each assessed using two different tests, the mean score for each pair of tests were calculated to give a composite measure of each child's orthographic knowledge and phonological-processing skill. These composite tests and the tests of sentence comprehension and general intelligence will be examined in relation to the simulation results that are reported below.

Results

Comprehension—The adults and children correctly answered 90% and 80% of the questions, respectively. Although this difference was significant [$t(89) = 2.63, p < 0.01$], both groups understood the text well about chance performance (i.e., 33%).

Eye-Movement Data—The raw eye-movement data were processed as necessary (e.g., to re-align individual fixations) using automated software². Following convention, fixations less than 80 ms or more than 1,000 ms in duration were excluded from the analyses, as were all fixations on the first and last words in each line of text³. Six dependent measures were then calculated for each of the words read by each participant, using only fixations that occurred during the first pass through the text: (1) *first-fixation duration (FFD)*, or the duration of the first of one or more fixations; (2) *single-fixation duration (SFD)*; (3) *gaze duration (GD)*, or the sum of all first-pass fixations; (4) the *probability of fixating once (Pr1)*; (5) the *probability of fixating two or more times (Pr2+)*; and (6) the *probability of skipping (PrS)*.

The mean fixation-duration and fixation-probability measures are shown in Figure 1A–B (for adults) and Figure 1C–D (for children) as a function of word frequency in printed text [tabulated using Lexique 3 (New, 2006) for the adults and Manulex (Lété, Sprenger-Charolles, & Colé, 2004) for the children] and the following five classes: (1) 1–10 per million; (2) 11–100 per million; (3) 101–1,000 per million; (4) 1,001–10,000 per million; and (5) 10,001+ per million. Two major trends emerge from the data. The first is a replication of the well-documented *word-frequency effect* (e.g., see Rayner, 2009): More frequent words are the recipients of fewer and shorter fixations than less frequent words. The second is a replication of the typical pattern related to reading skill (e.g., see Blythe & Joseph, 2011): Adults tend to make fewer and shorter fixations than children. The fact that our experiment replicated these two well-documented trends indicates that our method and materials were valid. In the sections that follow, we report the results of two simulations that

²This fixation realignment software was developed by Gelu Ionescu (gelu.ionescu@gipsa-lab.grenoble-inp.fr).

³Because of the fixations preceding and following return sweeps from one line of text to the next are not representative of other fixations (and thus outside of the theoretical scope of the E-Z Reader model), these words were excluded from our analyses and simulations.

were completed to explore the bases of such effects, in an attempt to better understand the relationship between reading acquisition and eye-movement patterns. Before doing this, however, it is first necessary to describe the model that was used to perform these simulations—E-Z Reader (for a review, see Reichle, 2011).

Simulations

In this section we first provide a brief overview of the E-Z Reader model of eye-movement control in reading (Pollatsek, Reichle, & Rayner, 2006; Rayner, Ashby, Pollatsek, & Reichle, 2004; Reichle, Pollatsek, Fisher, & Rayner, 1998; Reichle, Pollatsek, & Rayner, 2012; Reichle, Rayner, & Pollatsek, 2003; Reichle, Warren, & McConnell, 2009). We then report the results of simulations in which the model is used to examine the results of the experiments reported in the previous section.

E-Z Reader

The E-Z Reader model was designed to simulate the patterns of eye movements that are observed in skilled (adult) readers. Because the model has been described in detail elsewhere (e.g., for discussions of the model's assumptions and justification of its parameter values, see Reichle, 2011; Reichle et al., 2012; Reichle & Sheridan, 2015), the following description is only intended to provide the minimal amount of detail necessary to understand the simulations that are reported subsequently. Figure 2 is a schematic diagram of the model. As shown, the model specifies the visual, linguistic, and motoric processes that guide the eyes during reading. The two core assumptions of the model are that: (1) lexical processing is completed in a strictly serial manner, one word at a time; and (2) an early stage of lexical processing called the *familiarity check* initiates saccadic programming to move the eyes from one word to the next.

The mean time (in ms) required to complete the familiarity check on a word, $t(L_1)$, is a function of the printed word frequency (as tabulated by corpora; e.g., New, Pallier, Brysbaert, & Ferrand, 2004) and its within-sentence predictability (as determined by separate cloze-norm studies; see Taylor, 1953). More precisely, with a probability equal to word predictability, $t(L_1) = 0$ ms under the assumption that the word is “guessed” from its prior sentence context. However, because the majority of words are not predictable, in most instance $t(L_1)$ is specified by Equation 1:

$$t(L_1) = \alpha_1 - \alpha_2 \ln(\text{frequency}) - \alpha_3 \text{predictability} \quad (1)$$

In Equation 1, the three free parameters respectively control the maximal time required to complete the familiarity check on a word ($\alpha_1 = 104$), and how that time is attenuated by word frequency ($\alpha_2 = 3.5$) and word predictability ($\alpha_3 = 39$). Equation 1 thus gives the mean value of $t(L_1)$ for a word of a given frequency and predictability; the actual time during any given Monte-Carlo simulation run of the model is sampled from a gamma distribution⁴. Finally, the familiarity check is also modulated by visual acuity such that long words and

⁴The durations of all processes except the eye-brain lag (V in Fig. 2) and saccade execution (S in Fig. 2) are random deviates that are sampled from gamma distributions having means specified by the model's equations and standard deviations of 0.22 of the mean.

words far from the center of vision take more time to process than short words and words close to the center of vision. Equation 2 specifies this relationship:

$$t(L_1) \leftarrow t(L_1)\varepsilon^{\sum_{i=1}^N |\text{fixation-letter}_i|/N} \quad (2)$$

In Equation 2, the parameter ε ($= 1.15$) modulates the effect of visual acuity as a function of the mean absolute distance (in character spaces) between the fixation location and each letter i of the N letters of the word being processed. Finally, the time required to complete the second stage of lexical processing, corresponding to *lexical access*, $t(L_2)$, is given by Equation 3:

$$t(L_2) = \Delta[\alpha_1 - \alpha_2 \ln(\text{frequency}) - \alpha_3 \text{predictability}] \quad (3)$$

Thus, according to Equation 3, the time required to complete lexical access is some fixed proportion ($= 0.34$) of the time required to complete the familiarity check. As Figure 2 shows, as each word is identified, its meaning is integrated into the sentence representation while attention shifts to the next word so that lexical processing of it can be initiated.

Post-lexical integration on average requires $t(I) = 25$ ms to complete, but can fail with some probability ($p_F = 0.01$) or if integration of word n does not complete before word $n+1$ has been identified. Either type of integration failure causes the eyes and attention to be moved back to the source of difficulty, resulting in a pause and/or inter-word regression. As indicated, one of the core assumptions of E-Z Reader is that attention is allocated to support lexical processing in a strictly serial a manner, to exactly one word at any given time. The time required to shift attention from one word to the next on average requires $t(A) = 25$ ms.

The remaining model assumptions are all related to saccadic programming and execution. First, saccades are directed towards the center of words, or *optimal-viewing positions* (OVPs), or location from which words can be most efficiently identified (O'Regan & Lévy-Schoen, 1987). The length of the saccade that is actually executed, however, will be the sum of the programmed saccade length, some amount of systematic error, and some amount of random error. The systematic error causes long/short saccades to under/overshoot their intended targets, with the amount of such error decreasing as the launch-site fixation increases in duration. Equation 4 specifies this more formally:

$$\text{systematic} = (\Psi - \text{programmed}) \{[\Omega_1 - \ln(\text{duration})]/\Omega_2\} \quad (4)$$

In Equation 4, Ψ ($= 7$) is the length of the programmed saccade that the oculomotor system is biased to make, and Ω_1 ($= 6$) and Ω_2 ($= 3$) are free parameters that modulate the influence of the launch-site fixation duration. In a similar manner, random error is sampled from a Gaussian distribution with $\mu = 0$ and σ increasing linearly with the programming saccade length, as given by Equation 5 and its two parameters ($\eta_1 = 0.5$ and $\eta_2 = 0.15$):

$$\sigma = \eta_1 + \eta_2 \text{programmed} \quad (5)$$

Finally, for the sake of simplicity, saccades are assumed to require a constant $S = 25$ ms to execute. Upon fixating a new location, information from page is propagated from the eyes to the brain during a stage of pre-attention visual processing (i.e., V in Fig. 2) that takes 50 ms to complete, so that the constraints imposed by visual-acuity limitations on lexical processing (see Equation 2) can be updated from the new viewing location. An efference copy (Carpenter, 2000) of the programmed saccade length is used to rapidly calculate the absolute disparity between the intended saccade target, the *OVP*, and the actual fixation location so that this error can be used to (probabilistically) initiate a “corrective” refixation towards the center of the word. The probability of doing this, p , is given by equation 6 and its free parameter λ ($= 0.16$):

$$p = \max[\lambda | \text{fixation} - \text{OVP} |, 1] \quad (6)$$

As indicated, this description of E-Z Reader is not intended to be complete, but is instead only meant to give an overview of the model that is sufficient to understand the simulations that will be reported in the next sections of this article. In each of these sections, we first report the specific assumptions that were used in completing the simulations and then report the results of those simulations.

Simulation 1

Our first simulation was an attempt to replicate the key result reported by Reichle et al. (2013)—that the general pattern of eye movements in children could be simulated by increasing the value of α_1 (see Equation 1) to slow down the overall rate of lexical processing. The simulation thus attempted to simulate the six mean dependent measures for each of the five frequency classes of words that were observed with adults and children in our study (see Fig. 1). Although this goal may appear modest, it is important to emphasize that, apart from the parameters that control for lexical processing rate, all the other model parameters were set equal to their default values—as selected to fit adults reading English sentences rather than adults and children reading French passages. As such, the simulation represents an important test of how well the model’s assumptions generalize to other populations of readers and other languages and text materials.

Method—The simulations were completed using the lengths, frequencies, and cloze predictabilities (as determined by a separate normative study in which participants attempted to guess the identity of each word from its preceding sentence context⁵) of each word in our text. The best-fitting parameter values that were used in the simulations were found by completing grid searches of a parameter space defined by four parameters: α_1 , α_2 , α_3 , and . The goal was to determine which parameter values provided the best fit to the data of both the adults and children in our experiment. To that end, multiple grid searches were completed using increasing numbers of statistical subjects and smaller parameter increments across successive searches (as indicated in Table 3). Simulations were thus performed using each possible permutation of parameter values and the *root-mean-squared deviation*

⁵This normative study used 8 adults and 8 children who did not participate in our experiment (but who were selected from the same population) to determine the mean cloze-predictability values for each word in our text.

(*RMSD*) between the mean observed and predicted first-fixation durations, gaze durations, probabilities of fixating once, and probabilities of skipping to evaluate the model's goodness of fit to the observed data.

Results—The simulations results obtained with the best-fitting parameter values are shown in Figure 1, along with the participants' means to facilitate comparison. For the simulation of the adults' eye-movement patterns, an *RMSD* of 0.214 was obtained using the following best-fitting parameter values: (1) $\alpha_1 = 110$; (2) $\alpha_2 = 3.5$; (3) $\alpha_3 = 40$; and (4) $\alpha_4 = 0.2$. For the simulation of the children, the *RMSD* was 0.285 using the following best-fitting parameter values: (1) $\alpha_1 = 147$; (2) $\alpha_2 = 4$; (3) $\alpha_3 = 22.5$; and (4) $\alpha_4 = 0.2$. As inspection of Figure 1 shows, the model provided a reasonable fit to the observed data, resulting in *RMSD* values of comparable size to those previously reported (e.g., see Miellet, Sparrow, & Sereno, 2007). More importantly, the simulations replicate the key finding reported by Reichle et al. (2013)—that overall differences between the patterns of eye movements observed in beginning versus skilled readers can be explained by differences in the proficiency of lexical processing. Indeed, whereas the best-fitting value of the parameter that controls the overall rate of lexical processing in the simulation of the adults (i.e., $\alpha_1 = 110$) is comparable to previous values used to simulate adult readers (e.g., $\alpha_1 = 104$; Reichle et al., 2012), a considerably larger value of this parameter (i.e., $\alpha_1 = 147$) is required to fit the children's data.

To put these parameter values in context, consider how the two sets of best-fitting parameter values affect the rate of lexical processing in adults versus children. Using those values, the model predicts that the adults should on average require 151 ms to identify a 3-letter word having a frequency of 10,000 per million and 0 predictability if the center of the word is fixated (i.e., 151 ms = 50 ms for pre-attentive visual processing + 85 ms for the familiarity check + 16 ms for the completion of lexical access). However, the model predicts that children should require 193 ms to identify that same word (i.e., 193 ms = 50 ms for pre-attentive visual processing + 121 ms for the familiarity check + 22 ms for the completion of lexical processing). It is also worth noting that both of these estimates are consistent with physiological estimates of the time required to identify printed words (for a review, see Reichle & Reingold, 2013).

Interim Summary—Our first simulation demonstrates that the assumptions of the E-Z Reader model are general enough for the model to simulate the eye-movement patterns of French -speaking participants (thereby replicating Miellet et al., 2007), and of children (thereby replicating Reichle et al., 2013). The simulation that is reported next extends this work by using the model as a framework for examining the possible sources of variability in reading skills among our children participants.

Simulation 2

Our second simulation examined the possible source(s) of between-individual variability among children participants. To do this, the model was first fit to the six mean fixation-duration and fixation-probability measures of each child by selecting the best-fitting values of α_1 , α_2 , α_3 , and α_4 for each of the participants. Our goals in completing this simulation

were two-fold. First, our aim was to explore the model's ability to simulate (and hence possibly explain) the patterns of eye movements for each individual reader. Our second goal was to determine if the best-fitting parameter values were systematically related to the psychometric measures of reading ability that had been collected for each of the children. In line with our model's predictions, our hypothesis was that variability in values of α_1 would be systematically related to our participants' lexical knowledge, but would perhaps be unrelated to measures of sentence comprehension or general intelligence. We also explored whether values of α_1 would be more specifically related to orthographic knowledge or phonological-processing skill. Finally, providing that such relationships were observed, one might hope to provide a more definitive statement about the nature of the hypothesized familiarity check in the E-Z Reader model, such as whether it is based on orthographic information, phonological information, or some combination of the two.

Method—The general method used was very similar to that of Simulation 1. First, we completed grid searches of the model's parameter space to find parameter values giving the best fit between the 30 observed and simulated means (6 dependent measures $\times$ 5 frequency classes) for each of the 75 children. These grid searches were completed for the four parameters, parameter domains, and parameter increment sizes shown in Table 3.

Parameter Reliability—Three separate analyses were completed to assess the reliability of the individual estimated parameter values. First, we determined whether the best-fitting parameter values corresponded to RMSD minima. This was done by repeating the simulations while holding 3 of the 4 parameters equal to their best-fitting values while adjusting the fourth parameter by $\pm 10\%$, $\pm 20\%$, and $\pm 30\%$ around its best-fitting value. The resulting deviations between the RMSDs for the best-fitting and adjusted parameter values are shown in Figure 3. As the figure shows, the best-fitting values of α_1 and α_2 clearly contribute to smaller RMSD values, but this is much less true of both α_3 and α_4 . This latter finding suggests that it is necessary to exercise some caution in interpreting possible relationships between the values of the α_3 and α_4 parameters and other variables of interest (e.g., psychometric test scores).

Next, we performed a cross-validation to ensure that the results of our parameter estimation would generalize. This was done by splitting the eye-movement data into two sets: (1) the *training set* consisting of two thirds of the data that were used for estimating the best-fitting parameter values; and (2) the *testing set* consisting of the one third of the data used for evaluating the parameter-values obtained from the training set. (The data was divided into the two sets on a line-by-line basis so that the model would be fit to contiguous sequences of fixations.) The grid searches that were used to find the best-fitting parameters on the training set were completed using 1,000 statistical subjects per parameter set and the following parameters, parameter domains, and increments: (1) $\alpha_1 \in [90, 200]$, increment = 10; (2) $\alpha_2 \in [2, 6]$, increment = 1; (3) $\alpha_3 \in [10, 40]$, increment = 10; and (4) $\alpha_4 \in [0.2, 0.4]$, increment = 0.1. The entire process was then repeated 10 times to allow for stable results. As Figure 4 shows, the mean RMSD for the testing set was within 3 standard deviations of the mean RMSD for the training set, which indicates reliable parameter estimates. We also calculated both the inter-individual variability of the testing-set parameter values (i.e., the standard

deviation of the mean across the 10 runs for each of the 4 parameters for every child) and the intra-individual variability of testing-set parameter values (i.e., the mean of the standard deviations across the 10 runs for each of the 4 parameters for every child). The values of the former measure were approximately twice those of the latter for the parameters α_1 (ratio = 2.48), α_2 (ratio = 1.85), and α_3 (ratio = 2.08), suggesting that the estimates of the best-fitting values of these parameters were reliable. However, the values of α_3 exhibited much lower inter- than intra-individual variability (ratio = 0.395), which again suggests that caution is necessary when interpreting the values of this parameter.

Finally, to better understand how the RMSD values were related to the selection of the best-fitting values of α_1 , α_2 , α_3 , and α_4 , we examined their positions in 4-dimensional parameters space. This analysis indicated that, when the locus of the parameters that minimized the RMSD was inside the parameter space, the local evolutions of the RMSD as a function of the parameters were quadratic. In such cases, it is possible to conclude that a minimum RMSD value had been reached, and that a parameter had an impact of the evolution of the RMSD. However, for 21 of the 75 participants, the locus of the values of α_1 that minimized the RMSD was not inside the parameter space, indicating that the best value of α_1 had reached a limit defined by the parameter space, thus suggesting that the optimal value had not been found. Based on those findings, we decided to investigate the relations between the model parameters, the fixations measures, and the psychometric tests using only those children's data corresponding to the quadratic profile ($N = 54$). Although the data of the excluded 21 participants require further investigation and thus will not be discussed further in this paper, it is important to note that the boundaries of the parameter space were on some level arbitrarily selected to conform to a priori expectations about the minimum and maximum rates of lexical processing. As such, the decision to report our analyses using the restricted sample is conservative⁶.

Results—Of main interest are the values of the best-fitting model parameters and their relation to three other sets of variables: (1) the observed first-fixation and gaze durations; (2) the composite scores from the psychometric tests that were administered to the children prior to their participation in our eye-movement experiment; and (3) the scores measuring their comprehension of the text used in our experiment. (However, because our parameter-reliability analyses raised doubts about the reliability of the α_3 and α_4 parameters, we will forego any discussion of those two parameters.) The model's goodness-of-fit varied across the children, resulting in a range of RMSD values ($M = 0.41$; $SD = 0.13$; min. = 0.21; max. = 0.84). This variability was not surprising because the text included only 212 words (see Endnote 3), thus limiting the number of observed measurements per condition.

Table 4 shows the correlations among the best fitting-parameter values, the fixation-duration measures, psychometric test scores, and text comprehension scores. And similarly, Figure 5 contains six scatter-plots showing how the individual values of α_1 , the parameter that controls the overall rate of lexical processing, are related to the observed fixation-duration

⁶Analyses using the full set of children (i.e., $N = 75$) produced a similar pattern of results, with the only notable differences being that phonological-processing skill was also related to the best-fitting values of α_1 ($r = -0.36$; $p < 0.001$) and the two fixation-duration measures (first-fixation durations: $r = -0.32$; $p < 0.05$; gaze durations: $r = -0.40$; $p < 0.001$).

measures and composite test scores. As both Table 4 and Figure 5 show, the best-fitting values of the α_1 parameter are related to both the children's psychometric test scores and their mean fixation-duration measures, and with the latter two also exhibiting some inter-relationships. Each set of relations will now be discussed in turn.

First, consider the relationship between the best-fitting values of α_1 and the observed fixation-duration measures. Consistent with our interpretation of reading skill within the framework of the E-Z Reader model (Reichle et al., 2013), the values of α_1 are positively related to both first-fixation durations ($r = 0.86$) and gaze duration ($r = 0.77$). This suggests that, as the overall rate of lexical processing decreases (i.e., the value of α_1 increases), words tend to be the recipients of more, longer fixations.

Second, consider the relationships between the best-fitting values of α_1 and the psychometric test scores. The key findings here are that the values of α_1 are negatively related to orthographic knowledge ($r = -0.44$) and general intelligence ($r = -0.27$), but are not reliably related to our measures of phonological-processing skill ($r = -0.22$) or sentence comprehension ($r = -0.16$), or the children's specific text-related comprehension scores ($r = 0.13$). As interpreted within E-Z Reader, this pattern of associations suggests that skilled reading (as indicated by smaller values of α_1) may reflect better orthographic knowledge.

Finally, consider the relationships between the children's psychometric test scores and their fixation-duration measures. Here the key findings are that orthographic knowledge is negatively related to both first-fixation and gaze duration ($r = -0.26$ and $r = -0.59$, respectively), but that phonological-processing skill, sentence comprehension, and general intelligence are only related to gaze duration ($r = -0.35$, $r = -0.29$, and $r = -0.32$, respectively). This pattern of associations suggests that orthographic knowledge is tightly coupled to the initiation of saccadic programming (thereby modulating first-fixation durations), but that other variables (e.g., phonological processing skill) also influence the first-pass movement of the eyes through text (thereby modulating gaze durations). We will now discuss the theoretical significance of these findings.

General Discussion

The results of our simulations can be summarized as follows. First, Simulation 1 replicated two previously reported findings related to the E-Z Reader model. The first is that the theoretical assumptions of the model are general enough to simulate the patterns of eye movements observed with samples on French-speaking readers (Miellet et al., 2007). The second is that the model can straightforwardly explain both the similarities and differences that are observed in the eye movements of skilled (i.e., adult) and beginning (i.e., children) readers; doing so only requires the assumption that beginning readers are less proficient in lexical processing than skilled readers (Reichle et al., 2013). These results thus provide additional support for the claim that the E-Z Reader model provides a good approximate description of the perceptual, cognitive, and motoric processes that guide when and where people move their eyes during reading, and of how those processes might change with the development of reading skills (e.g., see Reichle & Sheridan, 2015). As has been discussed elsewhere (e.g., see Blythe, 2014), this has important ramifications for our understanding of

literacy and its development because relatively little work to date explored children's eye movements to understand what modulates eye-movement patterns when transitioning from beginning to skilled reading.

Simulation 2 extended the results of Simulation 1 by demonstrating that the E-Z Reader model can account for some of the between-individual variability that is observed in the eye movements of readers. Moreover, Simulation 2 revealed that the parameter values that allow the model to simulate individual readers are related to the children's fixation-duration measures and an important psychometric indicator of reading skill—orthographic knowledge. These findings suggest that the “decisions” about when to move the eyes off of a word during reading may also be influenced more by orthographic than phonological processing, and that the first stage of lexical processing in E-Z Reader (i.e., the familiarity check) might be conceptualized as being largely driven by fluency of orthographic processing (e.g., see Reingold, Sheridan, & Reichle, 2015). Although these conclusions are admittedly speculative because of the caveats that were previously discussed, they are consistent with results of eye-movement experiments showing that the duration of first-pass fixations on target words is influenced by the stimulus quality (e.g., faint vs. boldface font) of those words (Reingold & Rayner, 2006; Sheridan & Reingold, 2013).

These conclusions are also consistent with various possible “hybrid” implementations of the E-Z Reader model—implementations in which an existing word-identification model is embedded within the theoretical framework of E-Z Reader. Such a hybrid model would specify precisely how the process of identifying printed words “triggers” the initiation of a saccadic program to move the eyes from one word to the next. For example, the assumptions of the *multi-trace memory model* of Ans et al. (1998) provide one such possible instantiation. According to that model, words are represented as discrete memory traces that can be accessed via a retrieval process that is based on the overall similarity between the orthographic form of a printed word and the collective contents of long-term memory. Because this retrieval process provides a very natural index of word familiarity (e.g., how often a word has been encoded into long-term memory), it also provides a natural way to instantiate the familiarity check in E-Z Reader because frequently encountered words will provide a more rapidly available signal that their identification is imminent than will less frequently encountered words (e.g., see Reichle & Perfetti, 2003). Moreover, in such a hybrid model, the orthography will necessarily contribute more information to the familiarity signal than will phonological or semantic information because of the simple fact that it is available directly from the printed form of the word. This predicted differential effect of orthography versus phonology on word familiarity is therefore entirely consistent with the inter-relationships that were reported in this article among the best-fitting values of α_1 , the fixation-duration measures, and the composite measure of orthographic knowledge.

That being said, however, it is also important to acknowledge that proficient lexical processing is probably not the only determinant of reading ability. Indeed, our results hint at this conclusion because—as we indicated in our discussion of Simulation 2—we observed no relationship between the best-fitting values of α_1 and our measure of sentence comprehension, but observed a modest relationship between sentence comprehension and gaze duration. This pattern is intriguing because it suggests that, although first-fixation

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Figure 1.

Mean observed and simulated first-fixation durations (*FFD*), single-fixation durations (*SFD*), gaze durations (*GD*), and probabilities of fixating once (*Pr1*), two of more times (*Pr2+*), or skipping (*PrS*) for adults (Panels A & B) and children (Panels C & D), as a function of word frequency (counts per million).

Figure 2.

A schematic diagram of the E-Z Reader model of eye-movement control in reading (Reichle, 2011). The boxes represent information processing components of the model, and the arrows indicate how information and control of processing is passed among the components.

Figure 3.

The relative deviations between the optimal RMSD values and the RMSD values obtained using the best-fitting value of each parameter $\pm 10\%$ (blue), $\pm 20\%$ (green), and $\pm 30\%$ (red) of that value (while setting the other three parameters equal to their best-fitting values).

Figure 4. Box-plots showing the mean RMSD values resulting from cross-validation (across 10 iterations of training and testing).

Figure 5.

Scatter-plots showing the relationships between the individual best-fitting values of α_1 (plotted on the x -axis of each panel) obtained for the 54 children being simulated and: (A) first-fixation durations; (B) gaze durations; (C) orthographic knowledge; (D) phonological-processing skill; (E) sentence comprehension; and (F) general intelligence.

Table 1

Mean psychometric test performance accuracy and their standard deviations, their maximum possible scores, and the observed maximum and minimum scores for the $N = 31$ children excluded from our analyses due to, e.g., poor eye-tracker calibration, the $N = 21$ children excluded to poor parameter reliability, and the $N = 54$ included in our final analyses.

Descriptive Statistics	Inconsistent Word Spelling			Orthographic Lexical Decision			Pseudo-Word Spelling			Homophony Judgment			Sentence Comprehension			General Intelligence		
	31	21	54	31	21	54	31	21	54	31	21	54	31	21	54	31	21	54
N																		
Mean	21.0	21.1	22.3	34.5	34.6	34.3	11.8	14.0	13.3	13.6	14.9	14.3	8.9	11.8	10.3	32.0	38.0	35.4
Standard Deviation	8.2	6.1	6.7	5.0	5.1	5.2	4.8	2.8	2.7	3.7	3.5	3.4	5.4	3.8	4.7	9.0	5.0	6.0
Possible Maximum	37	37	37	42	42	42	20	20	20	21	21	21	24	24	24	60	60	60
Observed Maximum	34	32	36	41	41	42	17	19	19	19	20	20	19	18	20	48	48	49
Observed Minimum	1	12	2	22	20	13	2	8	5	5	5	6	1	2	0	19	29	21

Table 2

Inter-correlations among psychometric test scores.

Psychometric Tests	Inconsistent Word Spelling	Orthographic Lexical Decision	Pseudo-Word Spelling	Homophony Judgment	Sentence Comprehension	General Intelligence
Inconsistent Word Spelling	1.0					
Orthographic Lexical Decision	0.71 ***	1.0				
Pseudo-Word Spelling	0.43 ***	0.43 ***	1.0			
Homophony Judgment	0.51 ***	0.46 ***	0.45	1.0		
Sentence Comprehension	0.41 ***	0.46 ***	0.26 *	0.36 **	1.0	
General Intelligence	0.37 **	0.46 ***	0.36 **	0.48 ***	0.48 ***	1.0

Note:

* $p < 0.05$;

** $p < 0.01$;

*** $p < 0.001$.

Table 3

Number of statistical subjects, parameters, parameter domains, and parameter increment sizes used to find the best-fitting parameter values used in Simulations 1–3.

Grid Search #	Simulation 1						Simulation 2					
	Adults			Children			Children					
	# Statistical Subjects	Parameter	Domain	Increment Size	# Statistical Subjects	Parameter	Domain	Increment Size	# Statistical Subjects	Parameter	Domain	Increment Size
1	100	α_1	100–150	10	100	α_1	100–200	10	1,000	α_1	100–180	5
		α_2	1–4	1		α_2	1–4	1		α_2	2–4	0.5
		α_3	10–40	10		α_3	10–40	10		α_3	10–40	5
			0.2–0.6	0.1			0.2–0.6	0.1			0.2–0.4	0.05
2	1,000	α_1	95–115	5	500	α_1	120–150	5	N/A			
		α_2	2–4	0.5		α_2	3–4	0.5				
		α_3	20–40	5		α_3	10–40	5				
			0.2–0.4	0.05			0.2–0.4	0.05				
3	N/A				1,000	α_1	140–150	1				
						α_2	3–4	0.25				
						α_3	20–40	2.5				
							0.2–0.3	0.025				

Table 4

Relationships between best-fitting model parameters for the individual children participants ($N = 54$) and their mean fixation-duration measures, psychometric test scores, and text-comprehension scores.

Variables		Model Parameter Values		Observed Fixation-Duration Measures		Psychometric Test Scores			Text Comprehension
		α_1	α_2	FFD	GD	Orthography	Phonology	Comprehension	
Model Parameter Values	α_1	1.0							
	α_2	-0.10	1.0						
Fixation-Duration Measures	FFD	0.86***	-0.17	1.0					
	GD	0.77***	-0.30*	0.65***	1.0				
Psychometric Test Scores	Orthography	-0.44***	0.16	-0.26*	-0.59***	1.0			
	Phonology	-0.22	0.23	-0.17	-0.35**	0.62***	1.0		
	Comprehension	-0.16	0.03	-0.15	-0.29*	0.44***	0.36**	1.0	
	IQ	-0.27*	0.19	-0.16	-0.32*	0.47***	0.43***	0.50***	1.0
Text Comprehension		0.13	0.09	0.17	0.07	0.06	0.18	0.28*	0.27*

Notes:

- 1. *FFD* = first-fixation duration
- 2. *GD* = gaze duration
- 3. * $p < 0.05$;
- ** $p < 0.01$;
- *** $p < 0.001$.