E-Z Reader: An overview of the model and two recent applications

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E-Z Reader: An Overview of the Model and Two Recent Applications

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[-] Abstract and Keywords

In this chapter we review what is known about eye movements during reading and describe a computational model that simulates many of the perceptual, cognitive, and motor processes that guide readers' eye movements—the E-Z Reader model. We discuss how the model is being used to examine two fundamental questions related to reading: (1) What mediates the development of reading skill? (2) What is the time course of lexical processing? Simulations using the model suggest that very rapid lexical processing is necessary for skilled reading and that this processing must also be highly coordinated with other ongoing perceptual, cognitive, and motor processes. Thus a significant portion of the lexical processing of a word is completed while it is still in the parafovea (prior to the word being fixated). The implications of these conclusions are discussed, as are future directions in modeling the cognitive processes that control eye movements during reading.

Keywords: attention, computational model, development, eye movements, E-Z Reader, lexical processing, time course

> On the outside, the reader has rotated his eyes only a few millimeters … But on the inside, there has been a rapid succession of intricate events. Clearly, the succession could only be the product of a complex information processing system … It contains components that are asked to perform amazing feats with amazing rapidity, and precisely in concert.—Gough (1972, p. 341)

E-Z Reader is a computational model of eye-movement control in reading. As such, it provides a formal description of how the perceptual and cognitive processes that are involved with reading interact with each other and the systems that program and execute saccades to produce the patterns of eye movements that are observed during reading (Pollatsek, Reichle, & Rayner, 2006; Rayner, Ashby, Pollatsek, & Reichle, 2004; Reichle, Pollatsek, Fisher, & Rayner, 1998; Reichle, Rayner, & Pollatsek, 1999, 2003; Reichle, Warren, & McConnell, 2009). In this capacity it has already proven highly successful, simulating the various benchmark phenomena that are related to readers' eye movements and that have been used to evaluate such models (for a review, see Reichle, 2011), and having been used as an analytical framework to examine a variety of theoretical issues related to reading (e.g., how eye-movement control during reading may differ from eye-movement control in other visual-cognitive tasks; Reichle, Pollatsek, & Rayner, 2012). Perhaps more important, however, is the fact that the model is an existence proof showing how the serial lexical processing of words can be the engine moving the eyes forward during reading, thus allowing one to make sense of behavior that—because of its inherent complexity—would otherwise be difficult to interpret.

In the remainder of this chapter, we will first very briefly review what is known about the basic characteristics of eye movements during reading and explain why the endeavor of understanding and modeling reader' eye movements is a worthwhile enterprise. We will then describe the E-Z Reader model and how it has recently been used to understand two key areas of reading research—the developmental changes that occur as beginning readers become skilled adult readers, and the time course over which lexical processing occurs during natural reading of text. Finally, we will discuss a limitation of the E-Z Reader model and how future research might improve both it and other models of eye-movement control during reading.

Eye Movements During Reading

The eye movements that occur during reading are largely comprised of two basic components—the *saccades* or ballistic movements of the eyes from one viewing location to the next, and the *fixations* or intervals during which the eyes are relatively stationary. The majority of saccades move the eyes forward through the text, but approximately 10 to 15% are *regressions* that move the eyes back to previously fixated locations in the text. Because our eyes can only see fine detail in a small region of the retina called the *fovea*, readers must move their eyes from word to word, typically fixating 70 to 80% of words in a text at least once, and many words are fixated two or more times. Although fixations vary considerably in duration, ranging from 50 to 1,000 ms, most fixations are 200 to 250 ms in duration. Importantly, there is overwhelming evidence that a variety of variables related to both lexical and higher-level linguistic processing affect the durations and locations of fixations, thereby making the measurement of eye movements an ecologically valid method to examine the online cognitive processes that mediate text comprehension (for reviews, see Rayner, 1998; Schotter & Rayner, this volume).

Because eye movements reflect on-going lexical and higher-order linguistic processing during reading, it is important to understand the precise manner in which both types of processing relate to visual processing, on the one hand, and oculomotor control, on the other. Efforts to understand this eye–mind link have resulted in a small number of computational models of eye-movement control during reading, of which E-Z Reader—the model that will be the focus of this chapter—is just one example (for a review, see Reichle et al., 2003). Although these models are often been described as models of "eye-movement control" rather than of "reading" per se (e.g., see Rayner & Reichle, 2010), they attempt to specify how several basic perceptual, cognitive, and motor processes dynamically interact across time to generate the moment-to-moment patterns of eye movements that are observed during reading. For that reason, the models provide theoretical frameworks for thinking about how the patterns of eye movements that are observed during reading are generated by the various components that support reading comprehension. Two examples illustrating this claim will be provided later in this chapter, but first we will provide a detailed description of the E-Z Reader model.

The E-Z Reader Model

The model has two core assumptions. The first is that lexical processing is completed in a strictly serial manner, on one word at any given time. Within the framework of the model, this assumption effectively means that the type of attention that is required for lexical processing (e.g., by binding together the features that make up a word) is allocated in a strictly serial manner, to exactly one word at a time. Because of this assumption, the model is an instance of a more general class of *serial-attention models* (see Reichle, 2011), which can be contrasted to models in which attention is allocated as gradient to support the concurrent processing of multiple words (e.g., *Glenmore*: Reilly & Radach, 2006; *SWIFT*: Engbert, Nuthman, Richter, & Kliegl, 2005).

The second core assumption of the E-Z Reader model is that the completion of a preliminary stage of lexical processing called the *familiarity check* on a word normally initiates the programming of a saccade to move the eyes to the next word. This assumption can be conceptualized as a heuristic that skilled readers acquire to afford maximal reading efficiency. That is, by initiating saccadic programming prior to the completion of lexical access, the eyes will not remain fixated on a word during the time that is required to program a saccade, thereby increasing fixation durations unnecessarily (e.g., for a discussion of this heuristic, see Reichle & Laurent, 2006). However, the fact that the subsequent completion of lexical access on a word then causes attention to shift to the next word means that there is a decoupling between the movements of overt and covert attention. As will be explained below, this decoupling allows the model to explain a certain amount of slippage that seems to occur between where the eyes are located and what the mind is processing—as evidenced, for example, by the finding that words are fixated for shorter durations if they are previewed in the parafovea prior to being fixated (Rayner, 1975; Reingold, Reichle, Glaholt, & Sheridan, 2012; for a review, see Schotter, Angele, & Rayner, 2012).

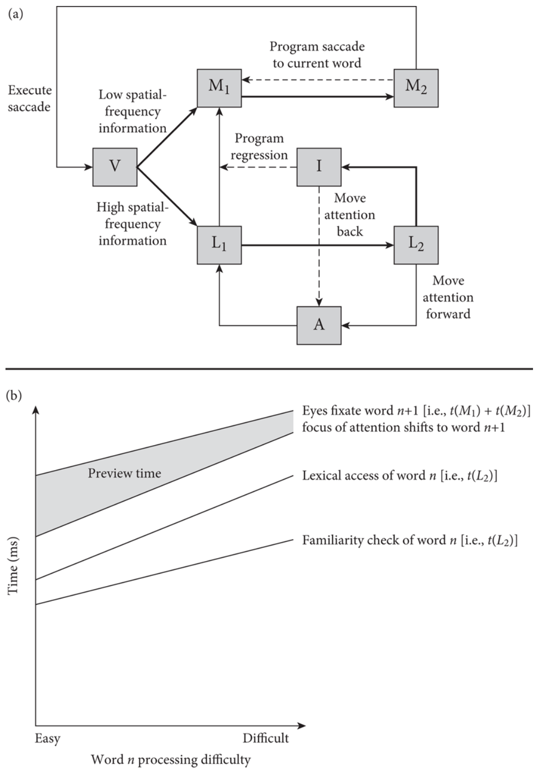

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Figure 1 Panel A is a schematic diagram of the E-Z Reader model of eye-movement control during reading. The labeled components are: (1) V = preattentive stage of visual processing; (2) L_1 = familiarity check; (3) L_2 = lexical access; (4) A = attention shift; (5) I = postlexical integration; (6) M_1 = labile stage of saccadic programming; and (7) M_2 = nonlabile stage of saccadic programming. The thick arrows represent the flow of information, the thin solid arrows show how the control of processing is obligatorily passed between model components, and the thin dashed arrows show how the control of processing can be probabilistically passed between model components. Panel B is a schematic diagram showing how parafoveal processing of word n+1 is modulated by the processing difficulty of word n (i.e., the fixated word). The x-axis shows the relative processing difficulty of word n, and the y-axis shows the mean time courses of key processes in the model, and how the slippage between when attention shifts to word n+1 and when the eyes move to word n+1 gives affords some amount of preview of that word. (The eye-mind lag would be expected to lengthen the preview time but this is ignored in the figure for convenience and because its duration is a constant.)

The two core model assumptions, in conjunction with several more specific assumptions about how the various processes involved in reading interact with each other to move readers' eye through text, form the framework of the model that is schematically illustrated in Figure 1A. That figure shows the various components of the model (represented by the gray boxes) and how both information and the control of processing are propagated through those components (represented by the arrows). These assumptions will now be explained in detail.

In the model, 50 ms is required for this propagation of information from the eyes to the mind, based on estimates of the eye-mind lag (for a review, see Reichle & Reingold, 2013). This stage of visual processing (labeled V in the model) is assumed to be preattentive because information is acquired from across the entire visual field, independent of where the focus of attention is located. But as Figure 1A shows, the two types of information are used for different purposes. Whereas the low spatial-frequency information (which is available in peripheral vision, where visual acuity is reduced) is used to segment upcoming words for the purposes of saccadic targeting, a smaller portion of the high spatial-frequency information (which is only available in central vision) is selected via attention for the purposes of lexical processing.

As already indicated, lexical processing is completed in two successive stages—the familiarity check (labeled L_1 in the model) and lexical access (labeled L_2). This distinction was originally motivated by dual-process theories of memory, in which the recognition of an item (e.g., word) can be based on two sources of information—a rapidly available sense of familiarity and a slower retrieval of information representing the item and the context in which it was encoded (e.g., see Yonelinas, 2002). Alternatively, L_1 and L_2 may be conceptualized as respectively corresponding to orthographic and semantic processing (Reingold & Rayner, 2006; Reingold, Yang, & Rayner, 2010). These two accounts are not mutually exclusive, so that, for example, word familiarity may be largely based on orthographic information.

In the model, the time (in ms) to complete the first stage of lexical processing for word *n*, $t(L_1)$, is given by Equation 1:

(1)

$$t\left(L_1\right)=\begin{cases}0 & \text{if } p<predictability_n\\ \alpha_1-\alpha_2\ln\left(frequency_n\right)-\alpha_3 predictability_n & \text{if } p\geq predictability_n\end{cases}$$

In Equation 1, the top branch represents instances in which a word is guessed from its preceding sentence context, allowing the familiarity check to be completed in 0 ms. This happens with a probability, *p*, equal to a word's cloze predictability, which is the mean proportion of time that the word is guessed from its preceding sentence context by a group of independent subjects (Taylor, 1953). The assumption that words can be guessed in this manner was motivated by the finding that in eye movement experiments during which only the word being fixated is visible (e.g., the letters in the nonfixated words are replaced by random letters), readers sometimes completely skip highly predictable words (e.g., high-frequency function words like the article *the*; Rayner, Well, Pollatsek, & Bertera, 1982). Such words are presumably skipped because the semantic or syntactic constraints on the words are sufficient for them to be identified using only minimal visual information about the word (e.g., its length).

However, except for these predictable words, the time required to complete the familiarity check is assumed to be a linear function of the logarithm of word *n*'s frequency of occurrence in printed text (as tabulated in various text corpora; e.g., Francis & Kučera, 1982) and its cloze predictability, as modulated by three free parameters shown in the bottom branch of Equation 1: $\alpha_1 = 104$, $\alpha_2 = 3.4$, and $\alpha_3 = 39$. (These and other parameter values were selected to optimize the model's goodness-of-fit to empirical data.) Thus, on average, the familiarity check will require less time to complete for frequent or predictable words.

Because there is considerable inherent variability in the time required to process a word, the time that is specified by Equation 1 is only the mean time that is required to complete the familiarity check for a word of a given frequency and predictability; the actual time to complete the familiarity check on such a word during any given Monte-Carlo simulation run of the model is a random deviate that is sampled from a gamma distribution. (The times required to complete several of the processes in the model are random deviates that are sampled from gamma distributions having a specified mean and a standard deviation equation to $\sigma\gamma = 0.22$ of the mean.) The time that is required to complete the familiarity check is then adjusted as a function of the mean *eccentricity* (i.e., the distance in character spaces) between the point of fixation and each of the letters of the word being processed, as specified by Equation 2:

(2)

$$t\left(L_1\right)\leftarrow t\left(L_1\right)\cdot\varepsilon^{\sum_{i=1}^{N}\left|fixation-letter_i\right|/N}$$

In Equation 2, the free parameter $\varepsilon = 1.15$ determines the absolute amount by which eccentricity modulates the slowing effect of limited visual acuity, with *i* in the exponent indexing each of the *N* letters in the attended words. Thus, according to Equations 1 and 2, with all else being equal, words that are frequent, predictable, short, or close to fixation will be the recipients of fewer, shorter fixations than words that are infrequent, unpredictable, long, or far from fixation, consistent with what is typically observed (Rayner, 1998; Schotter & Rayner, this volume).

Turning now to lexical access, the time (in ms) required to complete lexical access on word *n*, $t(L_2)$, is a fixed proportion ($\Delta = 0.34$) of the time required to complete the familiarity check, as specified by Equation 3:

(3)

$$t\left(L_2\right)=\Delta\left[\alpha_1-\alpha_2\ln\left(frequency_n\right)-\alpha_3 predictability_n\right]$$

In contrast to the familiarity check, lexical access always requires some nonzero amount of time to complete based on the assumption that it involves the activation of a word's meaning, irrespective of whether or not that meaning is activated from its prior sentence context, from visual input, or some combinations of the two. As was true of the familiarity check, the actual time that is required to complete lexical access during any Monte-Carlo simulation run of the model is a random deviate that is sampled from a gamma distribution.

As Figure 1A shows, the completion of lexical access simultaneously causes two things to happen. The first is that attention shifts from the word that was just identified to the next word, so that lexical processing (i.e., the familiarity check) of the next word can begin. The shifting of attention is not instantaneous, however; the time required to shift attention, $t(A)$, is a random deviate sampled from a gamma distribution having a mean determined by the free parameter A = 25 ms.

The second thing that happens when a word is identified is that postlexical *integration* of that word's meaning begins. This integration (labeled I in the model) is the minimal time required for the reader to know that the meaning of the identified word fits into the semantic and syntactic framework of the sentence representation that is being constructed. Because postlexical processing of a word is normally completed in the background of on-going lexical processing, and thus having no discernable affect on the progression of the eyes through the text, and because postlexical processing is not important for the two model applications discussed below, it will not be described in detail here. However, it is important to note that integration failure can cause the eyes and attention to move back to the location of integration failure (see Reichle et al., 2009), allowing the model to simulate the regressions observed with sentences that are syntactically ambiguous (e.g., Frazier & Rayner, 1982) or semantically implausible (Warren & McConnell, 2007) that are discussed more fully in Staub (this volume).

The remaining assumptions of the E-Z Reader model are all related to saccadic programming and execution. The first of these assumptions is that saccadic programming is completed in two successive stages—a labile stage (labeled M_1 in the model) that is subject to cancelation by the initiation of a subsequent saccadic program, following by a nonlabile stage (labeled M_2) that is not subject to cancelation. The motivation for this assumption was based on seminal experiments in which subjects were instructed to move their eyes as rapidly as possible from one cued location to another. These experiments which involved simple stimuli but complex situations in which saccades should be made or suppressed (e.g., Becker & Jürgens, 1979) showed that saccades are programmed in two successive stages.

In E-Z Reader, the times required to complete both the labile and nonlabile stages of saccadic programming are random deviates sampled from gamma distributions having means of $t(M_1)$ = 125 ms and $t(M_2)$ = 25 ms, respectively. This allows the model to explain word skipping. To understand how, imagine that the eyes and attention are on word n. At some point, the familiarity check on that word will complete, causing the initiation of a saccade program to move the eyes to word n+1. Lexical processing of word n will continue, however, until word n has been identified (i.e., the completion of L_2), causing attention to shift to word n+1 so that parafoveal processing of that word can begin. At this point, two things can happen. The first is that the labile saccadic program to move the eyes to word n+1 completes before the familiarity check on word n+1 completes; in this situation, the saccadic program has reached a point of no return and upon completion of the nonlabile stage the eyes will obligatorily be directed toward word n+1. The second possible situation is that the familiarity check on word n+1 completes before the labile saccadic program to move the eyes to word n+1; in the second situation, a second labile saccadic program (to move the eyes to word n+2) will be initiated, thereby canceling the first and resulting in the eyes eventually being directed to word n+2 and causing word n+1 to be skipped. This account of word skipping via the replacement of one saccadic program by another gives rise to the prediction of skipping cost, or inflated fixations immediately before skipped words—a prediction that has been partially confirmed (e.g., Kliegl & Engbert, 2005; see also Reichle & Drieghe, 2013).

The model also assumes that saccades are always directed toward the centers of words, but that the length of any given saccade will be a linear combination of three components, as indicated in Equation 4:

(4)

$$saccade\,length = intended\,saccade\,length + systematic\,error + random\,error$$

The intended saccade length is the actual distance (in character spaces) between the current fixation location and the saccade target (which is the center of whatever word the eyes are being directed toward). As Equation 5 shows, the systematic error (in character spaces) is a function of the disparity between the intended saccade length and an optimal saccade length ($\Psi = 7$), and the fixation duration on the launch-site word, $fixation_{LS}$. Thus saccades that are longer/shorter than seven character spaces will tend to undershoot/overshoot their intended targets by approximately half a character space of deviation, with the amount also modulated by the fixation duration on the launch site. ($\Omega_1 = 6$ and $\Omega_2 = 3$ are free parameters that control the degree to which the launch-site fixation duration modulates the systematic error.

(5)

$$systematic\,error = (\psi - intended\,saccade\,length) \cdot \{[\Omega_1 \ln(fixation_{LS})] / \Omega_2\}$$

And finally, the random error component in Equation 4 is a random deviate that is sampled from a Gaussian distribution with $\mu = 0$ character spaces and σ specified by Equation 6. In that equation, the free parameters $\eta_1 = 0.5$ and $\eta_2 = 0.15$ control the degree to which the variability of the random error component increases with the intended saccade length, so that long saccades are more prone to error than short saccades.

(6)

$$\sigma = \eta_1 + \eta_2 * intended\,saccade\,length$$

In combination, Equations 4-6 cause the distributions of fixation landing sites to resemble those reported in the literature—the distributions are approximately Gaussian in shape, centered near the middles of words but with missing tails that reflect instances when a saccade undershot/overshot its intended target and that increase in magnitude as the launch-site fixation duration decreases (e.g., McConkie, Kerr, Reddix, & Zola, 1988).

For the sake of simplicity, the model assumes that saccades require a constant $S = 25$ ms to execute. Although visual processing halts during the actual saccades (Matin, 1974), lexical processing continues at a rate determined by the intrinsic properties of the word being processed (i.e., its frequency and predictability; see Equations 1 and 3) and the eccentricity of saccade launch-site location (see Equation 2). Lexical processing then continues at its presaccade rate for an additional $V = 50$ ms after the eyes fixate their new viewing location (i.e., the duration of the eye-mind lag in the model). Because the time required to complete lexical access is some fixed proportion of the time required to complete the familiarity check (see Equation 3), and because the times required to complete saccadic programming, execute the saccade, shift attention, and propagate visual information from the eyes to the mind are (on average) constants, there is often a considerable amount of time available for parafoveal processing of word n+1 from a fixation on word n, but this time varies as a function of the processing difficulty of word n. The duration of the above processes determines the time that is available for parafoveal preview, as shown in Figure 1B. In this figure, the processing difficulty of word n is indicated along the x-axis, the process durations are indicated along the y-axis, and the amount of time available for previewing word n+1 from word n is indicated by the gray shading. As can be seen, preview of word n+1 is modulated by word n's processing difficulty. This allows the model to explain the finding that as the processing difficulty of word n increases, the time available for parafoveal processing of word n+1 decreases (e.g., Henderson & Ferreira, 1990).

The final assumption of E-Z Reader is related to automatic refixations, or rapid eye movements to a new viewing location following an initial fixation near the edge of a word. The motivation for this assumption is the fact that an initial fixation near the beginning and ending of a word affords a poor viewing location from which to process the word, and as such might be expected to result in a rapid movement of the eyes toward the center of the word, a location that affords more rapid and accurate lexical processing (O'Regan & Lévy-Schoen, 1987). According to the model, this propensity is based on efference copies of the saccadic programs that aim to move the eyes from one word to the middle of the next (Carpenter, 2000); to the extent that the intended saccade is prone to error and deviates from its target (see Equations 4–6, above), the probability of rapidly initiating a second, corrective saccade increases, as specified by Equation 7. The probability of initiating a corrective saccade (i.e., refixating) increases with the absolute distance (in character spaces) between the initial fixation position and the original saccade target (i.e., the center of the word being targeted), but is modulated by the free parameter $\lambda = 0.16$.

(7)

$$p(refixation) = \max(\lambda\,|landing\,position - saccade\,target|, \cdot 1)$$

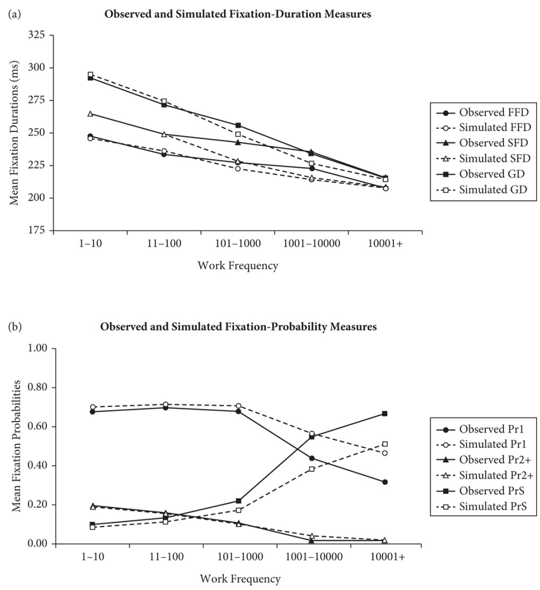

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Figure 2 Panel A shows the mean observed (solid lines) and simulated (dashed lines) first-fixation (*FFD*), single-fixation (*SFD*), and gaze durations (*GD*), for five frequency classes of words. Panel B shows the mean observed (solid lines) and simulated (dashed lines) probabilities of fixating once (*Pr1*), two or more times (*Pr2+*), and skipping (*PrS*) for five frequency classes of words.

The model as described above is able to simulate all of the benchmark findings that have been used to evaluate models of eye-movement control in reading (see Reichle et al., 2012). To give a specific example, Figure 2 shows the mean values of six commonly used word-based dependent measures for five frequency classes of words in a corpus of sentences used by Schilling, Rayner, and Chumbley (1998): (1) *first-fixation duration*, or duration of the first of one or more fixations on a word; (2) *single-fixation duration*, or duration of a fixation on a word that is fixated exactly once; (3) *gaze duration*, or the sum of all first-pass fixations on a word; (4) the probability of fixating a word exactly once; (5) the probability of fixating a word two or more times; and (6) the probability of skipping a word. All of the above measures are first-pass measures. That is, calculated using only fixations that occurred during the first pass through the sentences (i.e., excluding any fixations that occurred after inter-word regressions). As Figure 2 indicates, as a word's frequency of occurrence in printed text increases, the mean fixation duration measures on those words decrease, as do the mean probabilities of the words being fixated once or more than once.

The finding that both the propensity to fixate a word and the durations of those fixations is modulated by the word's frequency is extremely robust (Inhoff & Rayner, 1986; Just & Carpenter, 1980; Rayner et al., 2004; Schilling et al., 1998) and provides compelling evidence that the decisions about when to move the eyes from a word are sensitive to the local processing difficulty of that word (i.e., its frequency). As Figure 2 shows, the E-Z Reader model does a fairly good job of simulating the effects of word frequency in reading, thereby demonstrating how something that may seem as slow as lexical processing in a serial word-by-word model can none-the-less be the engine that controls the progression of the eyes through text.

Two Recent Model Applications

As already indicated, the E-Z Reader model has been used to examine a large number of theoretical issues related to reading (see Reichle, 2011). In this section, we will review two areas of research that have recently been examined using the model—the question of how reading skill develops, and an attempt to better understand the time course over which lexical processing occurs.

The Development of Reading Skill

A number of studies have examined the eye movements of beginning readers—eight- to 10-year-old children with two to four years of formal reading education and who are proficient at decoding words and who can silently read complete sentences, but at slower rates than adults, even when reading age-appropriate texts. The key results of these comparative studies are remarkably consistent: Relative to skilled adult readers, children typically read fewer words per minute, making more fixations that are longer in duration, shorter saccades, with a larger proportion of those saccades being regressions (for a review see Blythe & Joseph, 2011).

There have also been other documented differences between the eye movements of child versus adult readers. For example, relative to adults, children have a smaller *perceptual span*, or region of effective vision, being less able than adults to use parafoveal vision to identify letters, the features of letters, and the blank spaces between words (e.g., Häikiö, Bertram, Hyönä, & Niemi, 2009). Children's fixation durations are also modulated by word frequency (e.g., Blythe, Liversedge, Joseph, White, & Rayner, 2009) and fixation location (e.g., Joseph, Liversedge, Blythe, White, & Rayner, 2009) to a greater degree than are adults. And children are slower at detecting violations of semantic plausibility (e.g., *Robert used a hook to catch the horrible mouse*, where *mouse* is implausible) than adults, typically detecting such violations only after their eyes have moved from the implausible word (Joseph et al., 2008). Interestingly, however, children's fixation landing-site distributions on words are very similar to those of adults, suggesting that even beginning readers are targeting their saccades on a word in a manner similar to those of skilled readers (Joseph et al., 2008).

Two general accounts have been proposed to explain the observed differences between eye movements of children versus adult readers. According to the *oculomotor-tuning hypothesis*, these differences reflect the fact that children are less skilled at moving their eyes, possibly because they are slower at programming saccades or more prone to saccadic error (e.g., see Klein & Foerster, 2001). According to the alternative, *linguistic-proficiency hypothesis*, these differences reflect the fact that children are simply less proficient than adults at identifying printed words and integrating their meanings into linguistic representations (e.g., see Perfetti, 2007).

To evaluate the plausibility of the oculomotor-tuning and linguistic-proficiency hypotheses, a series of simulations were completed using the E-Z Reader model. In these simulations, the parameters that modulate the rate and manner of both saccadic programming and execution, on one hand, and lexical and postlexical processing, on the other, were systematically manipulated (Reichle et al., 2013). The goal in doing this was to first determine which parameters could be adjusted to produce the global pattern of eye movements observed with children (i.e., slower reading rates, longer fixations), and to then determine if the adjustments would be sufficient to account for the remaining similarities (e.g., similar fixation landing-site distributions) and differences (e.g., slower detection of semantic plausibility violations) that have been observed between children and adults.

The results of these simulations were straightforward but surprising—only increasing the value of the parameter that controls the overall rate of lexical processing (i.e., from $\alpha_1 = 104$ to $\alpha_1 = 208$; see Equation 1) was sufficient to generate the all of the findings related to children's eye movements except one. The one exception was the finding that children are slower than adults at detecting semantic-plausibility violations, often detecting such violations very late, as evidenced by the fact that their first-pass measures (e.g., gaze durations) are unaffected by these violations but their second-pass measures (e.g., total-viewing times) are (Joseph et al., 2008). To account for this final result, it was also necessary to assume that the children also require more time to complete postlexical integration than adults. This assumption, in combination with the slower overall rate of lexical processing for children than adults, was sufficient for the model to simulate the finding that children's first-pass fixation-duration measures were unaffected by semantic-plausibility violations, but that their second-pass measures were.

Thus on the basis of these simulations, one might conclude that the primary reason for the differences between the eye movements of beginning and skilled readers are differences in their proficiency in lexical—and to perhaps some lesser degree—postlexical processing. Although this conclusion is obviously tentative, it is interesting because it is consistent with prior claims that variation in the speed and accuracy of lexical processing is what mediates between-individual differences in reading skill (e.g., Ashby, Rayner, & Clifton, 2005; Perfetti, 2007; Shilling et al., 1998). That being said, we will now discuss how E-Z Reader has been used to examine the time course of lexical processing during reading.

The Time Course of Lexical Processing

Given the strong assumption that the rate of lexical processing accounts for both within- (i.e., developmental) and between-individual differences in reading skill, one might ask about the time course of lexical processing, and how it might vary both within and between individuals. This question has been the subject of considerable empirical research during the past several decades (e.g., see Reichle, Tokowicz, Liu, & Perfetti, 2011; Reingold et al., 2012; Schilling et al., 1998), in no small part because the estimates of the time required have often varied quite considerably across tasks. For example, one method of estimating the speed of lexical processing is to record reaction times on behavioral tasks, such as naming and lexical decision tasks. These tasks produce reaction times of approximately 500 to 700 ms (e.g., Schilling et al., 1998), but it is important to note that this time also encompasses nonlexical processes, including the motor and decision processes that support lexical decisions, and articulatory processes required for naming. Likewise, fixation times during reading are not a pure measure of the speed of lexical processing, because the dependent measures like gaze duration can also reflect additional processes, such as postlexical integration.

In an effort to provide more precise estimates of the speed of lexical processing during reading, recent research has employed distributional analyses, such as ex-Gaussian fitting (Staub, White, Drieghe, Hollway, & Rayner, 2010) and survival analyses (Reingold et al., 2012) to demonstrate that lexical variables (e.g., word frequency) can produce rapid effects on fixation durations during reading (for a review of these findings, see Reingold, Sheridan, & Reichle, this volume). Such rapid lexical effects are consistent with other work that employed neuroimaging methodologies (e.g., ERP, MEG) to demonstrate lexical effects within the range of 110 to 170 ms poststimulus onset (e.g., Assadollahi & Pulvermüller, 2001, 2003; Hauk, Davis, Ford, Pulvermüller, & Marslen-Wilson, 2006; Penolazzi, Hauk, & Pulvermüller, 2007; Reichle et al., 2011; Sereno, Brewer, & O'Donnell, 2003; Sereno, Rayner, & Posner, 1998; for a review, see Reichle & Reingold, 2013).

Although estimates of lexical processing time vary greatly, it is clear that a minimum interval of 100 to 150 ms is required before lexical processing is advanced enough to have a potential impact on fixation durations (Reichle & Reingold, 2013). However, because fixations are only 200 to 250 ms in duration, an important point of controversy has been whether lexical processing is fast enough to be the engine that drives eye movements (see Reingold et al., this volume). It is not immediately obvious how this could be true given that lexical influences are subject to severe temporal constraints—they must occur after the 50 ms eye–mind lag that occurs at the start of the fixation and before the 100 to 150 ms required to program a saccade that occurs at the end of a fixation. Because of these temporal constraints, it has been historically argued that word identification is simply too slow to have an impact on eye movements (Bouma & de Voogd, 1974; Kolers, 1976). As a result, a few of the current models of eye-movement control continue to assume that lexical processing plays only a minimal role in controlling eye movements (e.g., Feng, 2006; Yang, 2006).

Thus, given that the E-Z Reader model assumes that an early stage of lexical processing (i.e., L_1) is the engine that drives eye movements, it is important to demonstrate precisely how, according to the model, lexical processing can be rapid enough to have an impact on fixation durations. For example, the E-Z Reader model assumes that readers normally spend a substantial amount of time processing words to the right of fixation, thereby affording a significant amount of parafoveal processing (see Figure 1B). Specifically, the model predicts that, in many instances, the completion of lexical access (i.e., L_2) of word *n* allows attention to shift to word n+1 before the eyes actually move to word *n*+1, thereby making some amount of time available for the parafoveal processing of word *n*+1 from word *n*. The duration of this preview time includes whatever time is available between when attention first shifts to word *n*+1 and when new visual information from the fixation on word *n*+1 actually reaches the brain. This preview-time interval (i.e., the interval between when attention first shifts to word *n*+1 and the completion of the eye-mind lag from the new fixation on word *n*+1) could potentially provide a substantial amount of time for readers to initiate lexical processing of word *n*+1.

To examine the E-Z Reader model's predictions about parafoveal processing, Schotter, Reichle, and Rayner (2014) recently completed simulations to determine if the duration of preview time predicted by the model is sufficiently long to explain two interesting but controversial phenomena: (1) semantic-preview benefit; and (2) word *n*+2 preview effects. The former controversy is about whether readers can obtain semantic information about word *n*+1 while fixating word *n* (i.e., *semantic preview effects*) or whether it is instead only possible to obtain orthographic or phonological information. Although a number of studies have failed to show semantic-preview effects in English (Rayner, Balota, & Pollatsek, 1986; Rayner & Schotter, 2014; Rayner, Schotter, & Drieghe, 2014), a recent study by Schotter (2014) successfully demonstrated semantic-preview effects. This study used a gaze-contingent display-change method called the *boundary paradigm* (Rayner, 1975) to manipulate the letter information in the location of a target word prior to it being fixated. For example, prior to fixating the target word (e.g., *begin*), the reader might receive a preview that was identical to the target word (e.g., *begin*), a synonym of the target word (e.g., *start*), a semantically related word (e.g., *ready*), or an unrelated word (e.g., *check*). When the reader's eyes then crossed an invisible boundary to the left of a target word, the preview was immediately replaced by the target word. Using this paradigm, Schotter demonstrated that fixation durations on the target word were approximately the same for the identical- and synonym-preview conditions, and that both of these conditions produced faster fixation times than the unrelated-preview condition. This pattern of results therefore suggests that semantic information can be extracted from the parafovea, thereby allowing the meaning of word synonyms to be somehow integrated.

The second controversy mentioned above refers to the debate about whether parafoveal processing from word n can extend as far as word *n*+2 (i.e., *word n+2 preview effects*), or whether it is instead only possible to obtain information about word *n*+1. Although a number of studies have failed to show word *n*+2 preview effects (Angele & Rayner, 2011; Angele, Slattery, Yang, Kliegl, & Rayner, 2008; Rayner, Juhasz, & Brown, 2007), these effects have been demonstrated under some circumstances, such as when word *n*+1 is short and high in frequency (e.g., Kliegl, Risse, & Laubrock, 2007; McDonald, 2006; Radach, Inhoff, Glover, & Vorstius, 2013).

Although both semantic-preview effects and word *n*+2 effects might intuitively seem to be at odds with a model such as the E-Z Reader model (because of its strong assumption that attention is only allocated to one word at a time), the simulations reported by Schotter et al. (2014) demonstrated that neither effect is necessarily inconsistent with the model. These simulations used the standard version of the model and its default parameter values (see Reichle et al., 2012) to examine the model's predictions about the time spent engaged in the lexical processing of parafoveal words.

To examine semantic-preview effects using the model, Schotter et al.'s (2014) first simulation used the mean lengths, frequencies, and predictabilities of both the pretarget words and the synonyms of the target words that were used in Schotter's (2014) experiment. The results of this simulation were informative: The mean probability of previewing word *n*+1 (i.e., the word after the target word) was 0.94, the mean duration of that preview was 177 ms, and the mean probability of the word *n*+1 preview advancing to the L_2 stage of lexical processing was 0.08. Because the L_2 stage is hypothesized to encompass semantic processing, this last simulation result suggests that the model predicts some amount of semantic preview on a modest but nontrivial proportion of trials—consistent with the results reported by Schotter (2014).

To examine word *n*+2 preview effects, Schotter et al.'s (2014) second simulation examined the probability and time spent previewing word *n*+2 from word n while varying the lengths, frequencies, and predictabilities of words *n* and *n*+1 across a range of values. The key results of this second simulation were that the E-Z Reader model predicted some amount of parafoveal processing of word *n*+2 on 20% of simulation trials, but that this processing never advanced to the L_2 (i.e., semantic) stage. This pattern of results suggests that word *n*+2 preview effects should be limited to orthographic (and perhaps some amount of phonological) processing, but not semantic processing. The results of this second simulation in combination with the first therefore suggest that the E-Z Reader model can accommodate modest-sized semantic-preview and word *n*+2 preview effects, and the reason for this is that the model's assumptions affords a sufficient amount of time—but not too much time—for parafoveal processing of upcoming words.

Given the important role played by parafoveal processing in the E-Z Reader model, we were interested in knowing if the model's predictions about preview time would be congruent with the empirical estimates reported by Reingold et al. (2012). In that study, the frequency (i.e., high vs. low) and preview availability (i.e., available vs. not available) of target words was manipulated using the boundary paradigm (Rayner, 1975), such that readers either saw a preview of the target word (i.e., the *valid* preview condition) or a pronounceable nonword (i.e., the *invalid* preview condition). A survival-analysis technique was then used to provide estimates of the earliest influence of the word-frequency manipulation on fixation times in the valid and invalid conditions. The key finding was that the earliest influence of word frequency occurred (on average) 145 ms after the start of fixation on the target words in the valid preview condition, but occurred 256 ms after the start of the fixation on the target words in the invalid preview condition. This suggests that preventing the parafoveal preview of the target words slowed their lexical processing by approximately 111 ms (i.e., 256 - 145 = 111 ms). Therefore, based on these empirical estimates, it was important to know whether a simulation using the stimuli from the Reingold et al. (2012) experiment might produce equally long preview times, which could explain why lexical processing was dramatically faster in the valid than invalid preview condition.

Our simulation was completed using the lengths, frequencies, and predictabilities of the pretarget and target words used by Reingold et al. (2012), using the 48 sentences of the Schilling et al. (1998) corpus as frames for these words. (The target words were always located at the sixth word position in the sentence frames). Because we were also interested in knowing how preview time might be modulated by hypothesized differences in reading skill, we completed the simulations using two rates of lexical processing. This was done using the same two values of the α_1 parameter (see Equation 1) that were used to simulate beginning and skilled readers (i.e., α_1 = 104 ms for adults vs. α_1 = 208 ms for children; see Reichle et al., 2013). This new simulation otherwise used all of the model's default parameter values (see Reichle et al., 2012) and 1,000 virtual participants per simulated condition.

Our simulation yielded mean preview times of 158 ms in the skilled reading condition (i.e., α_1 = 104 ms) and 125 ms in the less-skilled reading condition (α_1 = 208 ms). Both of these predicted values are similar to the mean preview times obtained in the simulations reported by Schotter et al. (2014). More importantly, our simulation results suggest an important link between the rate of lexical processing and the amount of time that is available for preview, such that a slower rate of lexical processing affords less time for parafoveal processing of upcoming words. In other words, if word *n* requires more time to process because of a slower rate of lexical processing (or alternatively, because the word is low-frequency; Henderson & Ferreira, 1990), then there is necessarily a shorter interval of time available for the parafoveal processing of word *n*+1 (see Figure 1B). Furthermore, our simulated manipulation of reading skill also markedly affected the time available for preview, reducing it by 33 ms (i.e., 158 - 125 ms) in the less-skilled condition. Finally, if one subtracts the duration of the eye-mind lag (i.e., 50 ms) from the 158 ms preview time in the skilled-reading condition, the resulting estimate of preview time (i.e., 108 ms) is very consistent with Reingold et al.'s (2012) estimate of 111 ms based on survival analyses of fixation times.

Because the E-Z Reader model was not explicitly designed to produce preview times of a particular duration, our simulation results are important because they show that simulated preview times in excess of 100 ms are a nonintuitive by-product of the assumptions of the model. It is also impressive that the model's predictions about preview time can potentially accommodate a wide range of findings that the model was not originally designed to explain, such as semantic-preview effects, word *n*+2 preview effects, and the results of survival analyses of fixation times. Moreover, our simulation underscores the importance of actually running simulations to test one's predictions, rather than simply assuming that a model can or cannot account for nonintuitive findings (Rayner, Pollatsek, & Reichle, 2003). In this vein, we believe that future efforts should examine the model's intriguing prediction that differences in reading skill (as indexed by differences in the rate of lexical processing) can influence the amount of time that is available for parafoveal processing during reading.

Conclusions

During the last decade, the E-Z Reader model has motivated a large amount of new empirical research (e.g., Inhoff, Eiter, & Radach, 2005; Kennedy, 2008; Mitchell, Shen, Green, & Hodgson, 2008; Reichle et al., 2011; Reingold & Rayner, 2006; Reingold et al., 2010; Staub, 2011; White, Warren, & Reichle, 2011). We believe that this is largely due to the fact that the model provides a simple theoretical framework for thinking about eye-movement control in reading—a framework that is predicated on the basic assumption that words are (normally) identified one at a time, and that the decisions about when to move the eyes are linked to an early stage of word identification. That being said, it is also important to acknowledge that the model fails to provide any deep account of the many component processes that are involved in guiding readers' eye movements (e.g., attention, lexical processing; for discussions of this, see Rayner et al., 2003; Reichle et al., 2009). We therefore also believe that future models of eye-movement control will have to become more specific in their assumptions about how the various components involved in moving the eyes during reading (e.g., attention, lexical processing) are instantiated, perhaps by incorporating more detailed models of those processes within their frameworks.

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