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An Analysis of the Time Course of Lexical Processing During Reading

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Abstract

Reingold, Reichle, Glaholt, and Sheridan (2012) reported a gaze-contingent eye-movement experiment in which survival-curve analyses were used to examine the effects of word frequency, the availability of parafoveal preview, and initial fixation location on the time course of lexical processing. The key results of these analyses suggest that lexical processing begins very rapidly (after approximately 120 ms) and is supported by substantial parafoveal processing (more than 100 ms). Because it is not immediately obvious that these results are congruent with the theoretical assumption that words are processed and identified in a strictly serial manner, we attempted to simulate the experiment using the E-Z Reader model of eye-movement control (Reichle, 2011). These simulations were largely consistent with the empirical results, suggesting that parafoveal processing does play an important functional role by allowing lexical processing to occur rapidly enough to mediate direct control over when the eyes move during reading.

Keywords: Reading; Attention; Computational modeling; Distributional analyses; Eye movements; E-Z Reader; Lexical processing; Time course

1. Introduction

One of the long-standing questions in the psychology of reading has to do with the nature of the *eye–mind link* (for a review, see Reingold, Sheridan, & Reichle, 2014). At the heart of this question is an apparent paradox: Given that lexical processing and saccadic programming are relatively slow but fixations are short in duration, how could mental processes like word identification possibly be coupled to the moment-to-moment "decisions" about when to move the eyes during reading? This question is of central importance because eye movements have been extensively used to understand cognition

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during reading (Rayner, 1998, 2009) and, as such, the validity of this method is predicated on the basic assumption that the mind and eyes *are* tightly coupled. For that reason, it is important to have a precise understanding of the eye–mind link. In the remainder of this article, we will attempt to advance our understanding of this topic by reporting the results of computer simulations of a recent experiment that has provided important new information about the temporal constraints that are imposed by visual encoding, lexical processing, and saccadic programming during reading (Reingold et al., 2012). As will be described in detail below, these simulations were completed using the *E-Z Reader* model of eye-movement control during reading (for a review, see Reichle & Sheridan, 2014). Because this model assumes that individual words in a text are processed and identified one word at a time, in a strictly serial manner, the model is conceptually transparent and thus ideally suited to examine the theoretical consequences of the various timing constraints. And as will become apparent below, this transparency affords the possibility of specifying precisely how the various constraints are accommodated by the cognitive systems that support "the most remarkable specific performance that civilization has learned in all its history" (Huey, 1908, p. 6)—skilled reading.

As just indicated, Reingold et al. (2012) recently reported the results of an eye-movement experiment in which both the frequency and parafoveal preview of specific target words were manipulated. This was done by embedding high- and low-frequency target words (that were matched for length and were unpredictable from the prior sentence context) in sentences, and then using a type of gaze-contingent display change called the *boundary paradigm* (Rayner, 1975) to either allow or prevent normal preview of the target words prior to their actually being fixated. For example, in the valid preview condition, the target words were displayed normally so that subjects could, for example, engage in some amount of parafoveal processing of a target word from the pre-target word. However, in the invalid preview condition, the target words were replaced by pronounceable non-words prior to being fixated, thereby preventing normal preview of the target words from the pre-target word. Both these manipulations affected looking times on the target words: High-frequency words were the recipients of fewer, shorter fixations than low-frequency words, and the absence of preview increased the looking times on both types of words. Both these findings thus replicate prior reports (e.g., for reviews, see Rayner, 1998, 2009). However, the new and more theoretically significant findings from this experiment were obtained by using *survival-curve analyses* to examine the time course over which these two variables and a third—initial fixation location—had their effects on the fixation durations. To understand these findings and their significance, however, it is first necessary to explain survival-curve analyses and their application to eye movements during reading (for an introduction, see Reingold & Sheridan, 2014; see also Feng, Miller, Shu, & Zhang, 2001; Glaholt, Rayner, & Reingold, 2014; Inhoff & Radach, 2014; Reingold et al., 2012; Schad, Risse, Slattery, & Rayner, 2014; Sheridan, Rayner, & Reingold, 2013; Sheridan & Reingold, 2012a,b).

In medical research, a "survival curve" simply refers to the function describing the survival rate of some group over time (e.g., the proportion of cancer patients who are still alive during each year after they are first diagnosed with the illness). In the context of

Reingold et al. (2012)'s experiment, survival curves were used to describe the percentage of fixations remaining on the target words as a function of their duration. That is, for each 1-ms interval after initially fixating the target words, the percentage of fixations remaining on the words is their *survival rate*. For example, if t is the time in ms since the onset of a fixation on a given word, then the 100% survival rate for fixations on that word at $t = 0$ ms drops to 0% at approximately $t = 600$ ms. In Reingold et al.'s experiment, such survival rates were calculated for *first-fixation durations* (i.e., the duration of the initial fixation during first-pass reading) on target words as a function of three variables: (a) target-word frequency; (b) the availability of parafoveal preview; and (c) the location of the fixations. This last variable was operationally defined by first normalizing the initial fixation locations (i.e., by converting their spatial locations to z-scores) and then splitting those locations into two groups: "central" fixations having locations less than $|z|$ from the mean of the fixation-location distribution versus "outer" fixations having locations greater than or equal to $|z|$ from the mean. A bootstrap resampling procedure (Efron & Tibshirani, 1994) was then used to identify when each of the three aforementioned variables first reliably influenced the first-fixation survival curves. For example, one such analysis examined when target-word frequency first influenced the survival rates of fixations on those words. By determining when the survival rates are first influenced by a variable in this way, it was possible to infer when the variable first affected the "decisions" to terminate the fixations on the target words. Importantly, the results of these survival-curve analyses indicated rapid effects of all three independent variables. Because these effects are both numerous and complex, however, only the most theoretical relevant findings will be discussed here.

First, in the valid preview condition, where the target word was always visible from the pre-target word, high-frequency target words were the recipients of fewer, shorter fixations than low-frequency target words, replicating the well-documented *word-frequency effect* (Inhoff & Rayner, 1986; Just & Carpenter, 1980; Kliegl, Nuthmann, & Engbert, 2006; Rayner, Ashby, Pollatsek, & Reichle, 2004; Schilling, Rayner, & Chumbley, 1998). Survival-curve analyses indicated that the first discernable effect of target-word frequency was evident after only 145 ms. (In other words, there was a reliable divergence between the first-fixation duration survival curves for high- vs. low-frequency target words after only 145 ms.) Moreover, only about 9% of the total first fixations had durations that were too short to be affected by word frequency in the valid preview condition. The latter conclusion was also supported by ex-Gaussian analyses (for an introduction, see Staub, White, Drieghe, Hollway, & Rayner, 2010) that were also completed to examine how word-frequency affected the means (i.e., μ), variability (i.e., σ), and degree of positive skew (i.e., τ) of the distributions of first-fixation durations. These analyses indicated that the mean of the distribution of first-fixation durations was shifted to the right for low- as compared to high-frequency target words (i.e., $\mu_{HF} < \mu_{LF}$), indicating that the effect of word frequency was not limited to a small number of long fixations, but that it instead influenced the majority of fixations.

Second, in the invalid preview condition, where the target word was not visible prior to being fixated, the effect of word frequency on mean fixation durations was reliable but attenuated. Survival-curve analyses also indicated the first discernable effect of target-word frequency was only evident much later in time, after 256 ms, and that 60% of the fixations were too short to be affected by word frequency in the absence of normal preview. And in contrast to what was observed with valid preview, ex-Gaussian analyses indicated that word frequency only increased the degree of positive skew for low- as compared to high-frequency target words (i.e., $\tau_{HF} < \tau_{LF}$), having no reliable effect on the distribution means (i.e., $\mu_{HF} = \mu_{LF}$). Importantly, if the time when the survival curves diverge for high- versus low-frequency words is a "marker" for when lexical processing begins,[1] then the fact that there is a 111 ms difference between when these divergence points occur with versus without preview (i.e., 256 − 145 ms = 111 ms) suggests that parafoveal processing normally affords a significant amount of time for lexical processing —in excess of 100 ms.

Finally, there was also an effect of first-fixation location, with central fixations being longer in duration than outer fixations, replicating prior results (Kliegl et al., 2006; Nuthmann, Engbert, & Kliegl, 2005, 2007; Vitu, Lancelin, & d'Unienville, 2007; Vitu, McConkie, Kerr, & O'Regan, 2001). Survival-curve analyses also indicated that the divergence point for this fixation-location effect occurred very rapidly, after only 143 ms, but that this divergence point was not modulated by either word frequency or parafoveal preview. The absence of such interactions suggests that, whatever influence fixation location has on the decisions about when to terminate a fixation, this influence is non-lexical (i.e., perceptual and/or motoric) in nature. As such, it provides a point of contrast against which the lexical effects that were discussed in the previous paragraphs can be compared.

Reingold et al. (2012)'s results provide important temporal constraints on the possible rate of lexical processing and—perhaps more important—are a critical set of "benchmark" findings that any viable model of eye-movement control in reading should be able to explain. That being the case, we thought that it was important to determine if one of the most vetted of these models, E-Z Reader (Pollatsek, Reichle, & Rayner, 2006; Rayner et al., 2004; Reichle, Pollatsek, Fisher, & Rayner, 1998; Reichle, Warren, & McConnell, 2009), could provide such an account. Although a detailed description of the model will not be provided here (see Reichle, 2011), the model incorporates two theoretical assumptions that set it apart from other models of eye-movement control during reading.[2] As already mentioned, the first is that, according to the model, the kind of attention that is necessary to support lexical processing is allocated in a strictly serial manner, to only one word at any given time. The second is that, in the model, the completion of an early stage of lexical processing called the *familiarity check* is the "trigger" that initiates the programming of a saccade to move the eyes from one word to the next.

To more fully appreciate how these two assumptions work in tandem to control the normal progression of the eyes through text, imagine that the eyes are fixated on word n. At some point, enough lexical processing of that word will have been done to complete the familiarity check, which causes the oculomotor system to begin programming a saccade to word $n + 1$. While this saccade is being programmed, however, the lexical processing of word n continues up until the point where it is identified (i.e., lexical access), which then causes attention to shift to word $n + 1$, so that its processing can begin. Then, after some additional amount of time, the saccadic program completes, causing the eyes to move to word $n + 1$. Importantly, because attention moves to word $n + 1$ before the eyes do, the model predicts that some amount of time will be available for the parafoveal processing of word $n + 1$. Moreover, because the time required to program a saccade is (on average) a constant in relation to the time required to complete the familiarity check, but the time required to complete lexical access is not, the model also predicts that the time that will be available for parafoveal processing of word $n + 1$ will increase as the processing difficulty of word n decreases. This relationship is depicted in Fig. 1 and illustrates how the model accounts for the interaction between foveal load and parafoveal preview that has often been reported (Henderson & Ferreira, 1990; Kennison & Clifton, 1995; White, Rayner, & Liversedge, 2005).

With this brief introduction to the E-Z Reader model, it is now possible to explain the theoretical significance of Reingold et al. (2012)'s findings. Their significance has to do with the simple fact that the experimental results indicate that there are severe constraints on the possible time course of lexical processing during reading. Perhaps this can be best appreciated by considering Fig. 2, which shows a hypothetical time course of the perceptual, cognitive, and motor processes that—according to models like E-Z Reader—are thought to mediate the moment-to-moment decisions about when to move the eyes from one word to the next during reading. For the purposes of simplicity, these processes can

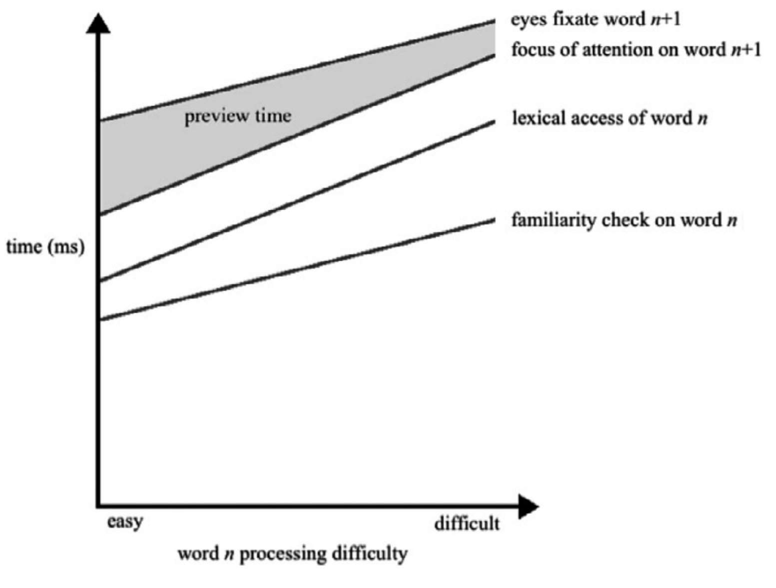

Fig. 1. The time course of lexical processing in the E-Z Reader model and its relation to foveal load and parafoveal preview. The x-axis shows the processing difficulty of the word being fixated (i.e., word n). The y-axis shows the mean times required to complete the familiarity check and lexical access on word n, and the mean times required to move both attention and the eyes to word $n + 1$. The shaded area shows the time available for parafoveal processing of word $n + 1$ from word n.

be divided into four groups, corresponding to the times required to (a) transfer information about the printed page from the eyes to the brain (i.e., the *retina–brain lag*); (b) process the visual features contained in that information (i.e., *visual encoding*); (c) complete whatever amount of lexical processing of a word is necessary prior to initiating a saccade (i.e., *lexical processing*); and (d) signal the oculomotor system to first program and then initiate a saccade to move the eyes to the next word (i.e., *saccadic programming*). Fig. 2 shows the sequence of these processes during a single 240-ms fixation (which corresponds to the mean duration reported by Reingold et al.), along with empirical estimates of the times required to complete each of the aforementioned processes based on experiments that have used electrophysiological methods (for a review, see Reichle & Reingold, 2013).

As Fig. 2A shows, the mean empirical estimate for the retina–brain lag is 60 ms after the onset of a stimulus. Similarly, the mean empirical estimates for the amount of time required to begin visual encoding and lexical processing are 92 and 148 ms, respectively. If these estimates are correct, then there is very little time remaining during a fixation for saccadic programming. For example, if a fixation lasts 240 ms, then there will only be 92 ms (i.e., 240–148 ms = 92 ms) to transmit the neural signal to the brainstem circuits that are responsible for programming and then executing a saccade. And if, as is posited in E-Z Reader, some amount of lexical processing must complete before the signal to begin saccadic programming can be initiated (i.e., an amount corresponding to the familiarity check), then this estimate of the time available for saccadic programming might be

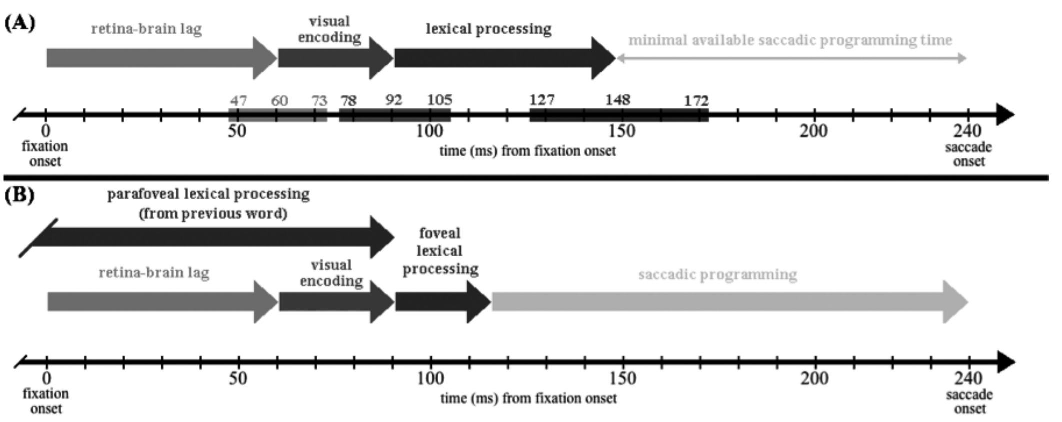

Fig. 2. A schematic diagram showing empirical estimates of the time course of the perceptual, cognitive, and motoric processes that are posited (e.g., by models like E-Z Reader) to control fixation durations on words during reading. Panel A shows the minimum, mean, and maximum empirical estimates of the times (in ms) required for the completion of the retina–brain lag, and for the initiation of visual encoding and lexical processing. As shown, the mean estimate of when lexical processing begins (i.e., after 148 ms) leaves only 92 ms for saccadic programming. Panel B shows that, with the introduction of a significant amount of parafoveal processing, the amount of foveal lexical processing that must be completed from the fixated word prior to initiating saccadic programming is markedly reduced, leaving ample time (in this example, 124 ms) for saccadic programming.

expected to be reduced even more. Importantly, such estimates of the time required for saccadic programming are shorter than current empirical estimates (e.g., Becker & Jürgens, 1979) and, as such, represent the crux of the eye–mind paradox that was mentioned at the beginning of this article—the fact that it is not immediately obvious how the eyes can be tightly coupled to the mind given that both lexical processing and saccadic programming are sluggish but fixations are relatively short in duration.

One possible solution to the above quandary is depicted in Fig. 2B, which shows the same sequence of processes as in Fig. 2A, but with some amount of parafoveal processing being included from each fixation. As the figure makes clear, by allowing a significant amount of lexical processing of a word from the prior word, the amount of lexical processing that may have to be completed from a given word prior to initiating saccadic programming (e.g., the familiarity check in E-Z Reader) is significantly reduced. For example, the figure shows that, with the introduction of significant parafoveal lexical processing (e.g., approximately 100 ms), the amount of foveal lexical processing that is sufficient to initiate saccadic programming is reduced to 25 ms, leaving ample time (124 ms) for saccadic programming. Given this preliminary theoretical analysis, the empirical question therefore becomes: How much lexical processing is normally completed from the parafovea?

Unfortunately, there is no simple answer to this question. There are, however, several factors that merit consideration because they might suggest a tentative answer. The first is that the temporal constraints depicted in Fig. 2B obviously put the most severe demands on eye-movement models that, like E-Z Reader, posit the serial allocation of attention (e.g., *Attention–Shift Model*: Reilly, 1993; *EMMA*: Salvucci, 2001; *Reader*: Just & Carpenter, 1987; Thibadeau, Just, & Carpenter, 1982; for a review of these models, see Reichle, 2011). The reason for this is that, to the extent that these models assume that some amount of lexical processing is completed in a strictly serial manner, this processing becomes the "bottleneck" that delimits when during a fixation saccadic programming can be initiated. Of course, these hard constraints are for that exact same reason relaxed to the degree that two or more words are processed in parallel. For example, these constraints are relaxed to some small degree even in the strictly serial E-Z Reader model because the time that is required to complete the retina–brain lag is largely "invisible" (i.e., has no discernable effect on lexical processing or fixation durations) because of the model's assumption that pre-attentive visual information is extracted from the printed page across the entire visual field; this pre-attentive visual processing therefore allows the features of an upcoming word to be available for lexical processing when attention shifts to the location of that word.

And of course the timing constraints depicted in Fig. 2 may be even less of a problem if multiple words are lexically processed and identified in parallel, as posited by attention–gradient models of eye-movement control (e.g., *Glenmore*: Reilly & Radach, 2003, 2006; *SWIFT*: Engbert, Nuthmann, Richter, & Kliegl, 2005; Schad & Engbert, 2012). For example, in the limit, completely parallel processing of words (i.e., processing that even ignores the limits of visual acuity) would likely cause individual fixation durations to equal the time required to program saccades because words would be identified equally well from any viewing location. The simple fact that this does not happen indicates that lexical processing is not completely parallel. This conclusion is also supported by evidence that limitations in visual acuity in turn delimit the amount of lexical processing that can be completed from the parafovea; for example, Rayner and Morrison (1981) demonstrated that words displayed in isolation at various foveal eccentricities are identified more slowly and less accurately as the distance between the center of vision and the center of the word increases.

There are also numerous demonstrations that the *perceptual span*, or the “region from which useful information can be obtained during a fixation in reading” (Rayner, 1986; p. 212), is severely limited (for a review, see Schotter, Angele, & Rayner, 2012). The most convincing of these demonstrations use gaze-contingent paradigms like the boundary paradigm discussed earlier (Rayner, 1975) to determine the quantity and type of information that can be extracted from parafoveal vision. For example, several such experiments have shown that the perceptual span is actually quite restricted in alphabetic languages like English: Although information about word boundaries (i.e., the blank spaces in between words) is on average available up to 15 character spaces to the right of fixation, information about letter shapes (e.g., the presence of ascenders vs. descenders) is on average only available up to 10 or so spaces, whereas information about the identities of individual letters (e.g., whether a given letter is an “e” or “c”) is on average only available up to seven or eight letter spaces (McConkie & Rayner, 1975, 1976; Rayner & Bertera, 1979). Of course, as indicated, these estimates are only averages; the precise amount of information that is extracted during a given fixation is influenced by a variety of cognitive variables (e.g., the difficulty of the fixated word; Henderson & Ferreira, 1990; Kennison & Clifton, 1995; White et al., 2005).

The conclusion that the perceptual span reflects a cognitive (e.g., attention) limitation rather than limited visual acuity is also indicated by three important demonstrations. The first is that, in languages that are read from right to left (e.g., Hebrew), the perceptual span extends asymmetrically to the left of fixation, rather than to the right, as in languages like English (Pollatsek, Bolozky, Well, & Rayner, 1981). The second is that the perceptual span is even more restricted for languages that have spatially compact writing systems (e.g., Japanese) because the relevant units of linguistic information (e.g., characters) are denser than in alphabetic languages like English (Osaka, 1989). And finally, there is evidence that the perceptual span increases with the development of reading skill; as children go from being beginning readers to skilled adult readers, their perceptual span increases (Häikiö, Bertram, Hyönä, & Niemi, 2009; Häikiö, Hyönä, & Bertram, 2010; Rayner, 1986). (This latter finding cannot be due to changes in visual acuity because the visual systems of reading-aged children are fully developed.)

More recently, there have been interesting demonstrations that are also informative about the time course and spatial extent of the perceptual span. The first of these demonstrations provides information about the time course of parafoveal processing, and more specifically, how the time that is available for such processing delimits the type of information that can be extracted from the parafovea. Although there have been numerous demonstrations that both orthographic and phonological information can be extracted from a word in the parafovea (see Schotter et al., 2012), these demonstrations have also indicated that parafoveal processing does not normally advance to the stage that would permit the extraction of semantic information. This conclusion may have been premature, however, because there is now evidence that—under some conditions—readers can extract parafoveal semantic information. For example, there is now evidence of these *semantic-preview effects* in both Chinese (Yan, Richter, Shu, & Kliegl, 2009; Yang, 2013; Yang, Wang, Tong, & Rayner, 2010) and German (Hohenstein & Kliegl, 2014; Hohenstein, Laubrock, & Kliegl, 2010). And similarly, Schotter (2013) also found a semantic-preview effect in English when the preview was a synonym of the target word (e.g., the preview "begin" for the target "start"). These findings collectively indicate that parafoveal words can sometimes be processed to the level of their meaning—a conclusion that (on some level) should not be too surprising given that words are often skipped, thereby suggesting that they have received enough parafoveal processing for the reader not to fixate them.

The second of these demonstrations is informative about the spatial extent of parafoveal processing. Although the studies cited in the previous paragraph indicate that the "spotlight" of attention is sufficiently large enough to encompass the parafoveal word (i.e., word $n + 1$, if word n is designated as the fixated word), there have been several studies that have attempted to determine if it also encompasses word $n + 2$. Although several of these studies have failed to find evidence of $n + 2$ *preview effects* (Angele & Rayner, 2011; Angele, Slattery, Yang, Kliegl, & Rayner, 2008; Rayner, Juhasz, & Brown, 2007), a recent experiment reported by Radach, Inhoff, Glover, and Vorstius (2013) observed $n + 2$ preview when word $n + 1$ was short and high frequency. And similarly, in Chinese, where most written words are comprised of one or two characters and not demarcated by blank spaces, $n + 2$ preview effects have been reported, but only when word $n + 1$ was visible (i.e., not masked) and high frequency (Yan, Kliegl, Shu, Pan, & Zhou, 2010) or a function word (Yan et al., 2009). ($N + 2$ preview effects were not observed when word $n + 1$ was low frequency; Yan et al., 2010; Yang, Rayner, Li, & Wang, 2012). The available evidence thus suggests that, at least when word $n + 1$ is short or otherwise easy to process, the spatial extent of the perceptual span is sufficient to afford some amount of parafoveal lexical processing of word $n + 2$.

Taken together, the above findings constitute important "benchmark" phenomena related to parafoveal processing and the time course of lexical processing during reading. Although the remainder of this article will primarily report our attempts to account for these findings using the E-Z Reader model of eye-movement control in reading (Reichle, 2011; Reichle & Sheridan, 2014), it is important to emphasize that the findings really do represent phenomena that any viable model should be able to explain. In other words, although the above phenomena do provide hard temporal constraints on the assumptions of models that, like E-Z Reader, posit a serial, staged architecture (e.g., EMMA: Salvucci, 2001), those same phenomena also represent (potentially) difficult challenges for models that, like SWIFT (Engbert et al., 2005), posit parallel lexical processing.

In the remainder of this article, we will first provide a brief description of the E-Z Reader model (Reichle, 2011; Reichle & Sheridan, 2014). We will then report the results of two new simulations that are intended to more carefully examine the time course of lexical processing. These simulations represent an attempt to explain the results reported by Reingold et al. (2012) in their survival-curve analyses of the effects of word frequency, preview availability, and fixation location. Our goal in completing these simulations was to provide a concrete account of the time course of lexical processing using the E-Z Reader model (and its assumption about serial lexical processing) as a theoretical framework. With that background, we will now describe the E-Z Reader model.

2. E-Z Reader

As previously indicated, the E-Z Reader model assumes that words are processed and identified in a strictly serial manner, and that an early stage of lexical processing called the familiarity check triggers saccadic programming to move the eyes forward. These core assumptions of the model are depicted in Fig. 3, which provides a schematic illustration of the main components of the model (which represent various perceptual, cognitive, and motor processes), and how both information and control are passed among those components to determine when and where the eyes move during reading. Because detailed descriptions of the model have already been published elsewhere (e.g., see Reichle, 2011; Reichle, Pollatsek, & Rayner, 2012; Reichle et al., 2009), we will not provide one here; our description will instead focus exclusively on those aspects of the model that are necessary to understand the simulation results reported below (e.g., we will not describe the model's post-lexical integration stage because it does not play a role in the theoretical questions being addressed by our simulations).

Of central importance to the present simulations is that the model assumes that lexical processing is accomplished in two discrete stages of processing: L_1 (i.e., the familiarity check) and L_2 (i.e., lexical access). The completion of the initial L_1 stage on word n indicates that lexical access of that word is imminent, which then triggers the programming of a saccade to move the eyes to word $n + 1$. The subsequent completion of the L_2 stage corresponds to accessing that word's meaning, which then causes attention to shift from word n to word $n + 1$. This decoupling of the shifting of attention from the movement of the eyes allows the model to explain parafoveal preview, which occurs whenever attention moves to word $n + 1$ before the eyes do. As previously explained (e.g., see Fig. 1), the amount of time available for previewing word $n + 1$ varies as a function of the processing difficulty of word n: Because a difficult-to-process word requires more time to identify than an easy-to-process word, attention will (on average) shift from a difficult word later than it will from an easy word, thereby diminishing the preview from difficult words. The present simulations were intended to test if these theoretical assumptions about parafoveal preview are sufficient to accommodate Reingold et al. (2012)'s results suggesting that a substantial amount of preview is necessary for lexical processing to

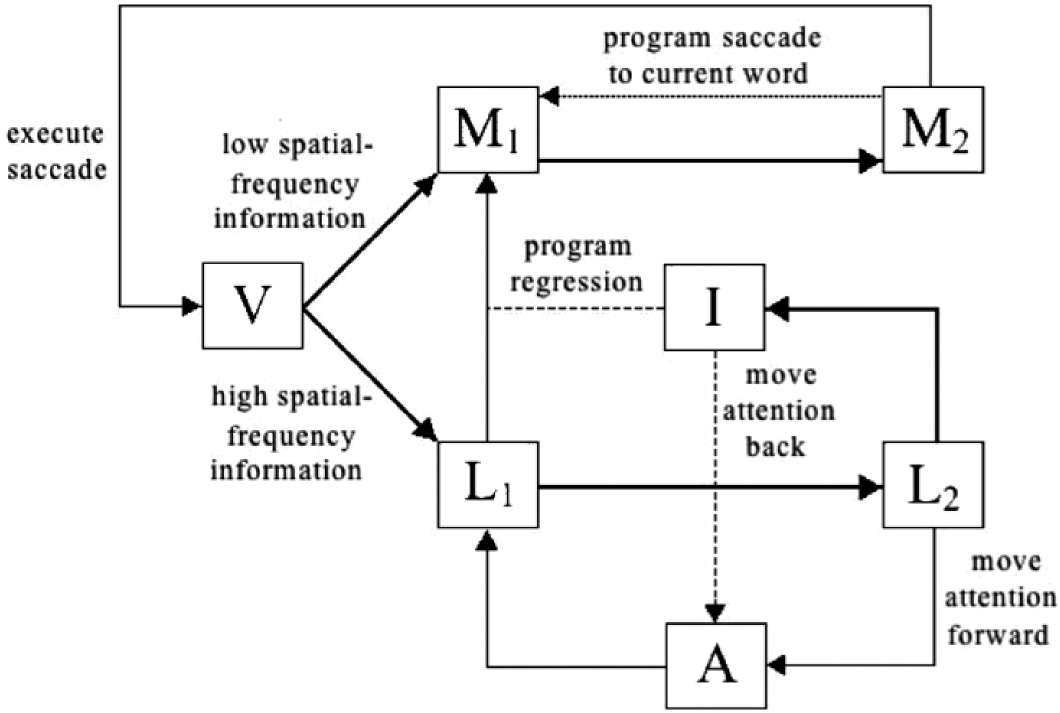

Fig. 3. Schematic diagram of E-Z Reader. The white boxes show the model components, which are as follows: (a) V = pre-attentive visual processing; (b) L_1 = familiarity check; (c) L_2 = lexical access; (d) A = attention shift; (e) I = post-lexical integration; (f) M_1 = labile stage of saccadic programming; and (g) M_2 = non-labile stage of saccadic programming. The thick black arrows indicate how information is propagated between model components, the thin black arrows indicate how control is passed between components, and the thin dotted arrows indicate control that is passed only occasionally (e.g., with regressive saccades).

mediate direct control over the "decisions" about when to move the eyes during reading. Before we describe those simulations, however, it is first necessary to first explain the model's assumptions about lexical processing, attention, and the programming and execution of saccades.

First, according to E-Z Reader, the time (in ms) required to process and identify a word varies as a function of its frequency of occurrence in printed text (measured using corpora; see e.g., Brysbaert & New, 2009; Francis & Kucera, 1982) and its within-sentence contextual predictability (measured using cloze-task norms; Taylor, 1953), as specified by Eq. 1. Thus, with a certain probability equal to word *n*'s predictability, $predictability_n$, the word is "guessed" from its context and the time required to complete L_1, $t(L_1)$, is set equal to 0 ms. However, because the vast majority of words are not predictable from their context, the time required to complete L_1 is most often determined by the bottom "branch" of Eq. 1, where $t(L_1)$ is a linear function of the natural logarithm of word *n*'s frequency, $frequency_n$, and its predictability.

$$t(L_1) = \begin{cases} 0 & \text{w}/p = \mathit{predictability}_n \\ \alpha_1 - \alpha_2 \ln(\mathit{frequency}_n) - \alpha_3 \mathit{predictability}_n & \text{otherwise} \end{cases} \quad (1)$$

In Eq. 1, $\alpha_1(= 104)$, $\alpha_2(= 3.5)$, and $\alpha_3(= 39)$ are free parameters that, respectively, control the maximal time required to complete L_1, and how that time is attenuated as a function of a word's frequency and predictability. These parameter values (and others) are selected to optimize the model's goodness-of-fit to empirical data. Thus, the indicated default values were selected to optimize the model's capacity to simulate the data of college students reading single sentences in an eye-movement experiment reported by Schilling et al. (1998). However, in previous simulations, the values of these parameters have been adjusted to allow the model to fit the data from experiments involving other populations of readers and text materials. For example, to simulate the patterns of eye movements observed with beginning readers (i.e., children), the value of α_1 was increased to slow the overall rate of lexical processing (Reichle et al., 2003). Similarly, to simulate the eye movements of elderly readers, the values of α_1 and α_2 were increased to (respectively) slow lexical processing and increase the degree to which it is modulated by word frequency (Rayner, Reichle, Stroud, Williams, & Pollatsek, 2006). And most recently, the values of α_1 have been shown to correlate with between-individual variability in both eye movements and psychometric measures of orthographic knowledge of a large sample of children (Mancheva et al., in press).

In a manner similar to what was described for L_1, the mean time required to complete L_2, $t(L_2)$, is some fixed proportion of the time required to completed $t(L_1)$, as specified by Eq. 2. In this equation, $\Delta(= 0.34)$ is a free parameter that specifies the precise proportion of $t(L_1)$ (as specified by the lower branch of Eq. 1) that is required to complete L_2. The lower branch of Eq. 1 is used under the assumption that the completion of L_2 corresponds to the process of activating a word's meaning, which, irrespective of how predictable the word is, requires some non-zero amount of time to complete. The combination of Eqs. 1 and 2 allows the model to explain the ubiquitous findings that words that frequently occur in printed text and/or that are predictable from their preceding sentence context tend to be identified more rapidly and be the recipients of fewer, shorter fixations than words that occur infrequently and/or that are not predictable (e.g., Kliegl et al., 2006; Rayner et al., 2004; Schilling et al., 1998).

$$t(L_2) = \Delta[\alpha_1 - \alpha_2 \ln(\mathit{frequency}_n) - \alpha_3 \mathit{predictability}_n] \quad (2)$$

It is important to emphasize that Eqs. 1 and 2 give the mean values of $t(L_1)$ and $t(L_2)$ for words of a given frequency and predictability. However, during a given Monte Carlo simulation run of the model, the actual values of $t(L_1)$ and $t(L_2)$ are sampled from gamma distributions with means equal to the values given by Eqs. 1 and 2 and with a $SD = 0.22$ of those means. Furthermore, one of the model's assumptions is that the time required to complete L_1 is also modulated by limitations in visual acuity, as determined using the mean absolute distance between each of the letters in the word being processed and the center of vision (i.e., the fixation location). The precise manner in which this is done specified by Eq. 3:

$$t(L_1) \leftarrow t(L_1)\varepsilon^{\sum_i^N |fixation - letter_i| / N} \quad (3)$$

In Eq. 3, ε(= 1.15) is a free parameter that determines the absolute amount by which eccentricity modulates the slowing effect of limited visual acuity, and *i* indexes each of the *N* letters in the attended word. Eq. 3 thus allows the model to explain why words that are short or close to the center of vision require less time to identify and are the recipients of fewer, shorter fixations than words that are long or far from the center of vision (e.g., Rayner & Morrison, 1981).

Next are E-Z Reader's two assumptions about attention. The first has already been mentioned—that attention is allocated in a strictly serial manner, to exactly one word at any given time. The second is that attention requires some amount of time to shift from one word to the next. In the model, the time needed to shift attention, $t(A)$, is also a random deviate that is sampled from a gamma distribution with a mean of 25 ms and a SD = 0.22 of the mean.

Finally, according to E-Z Reader, saccades are programmed in two discrete stages—an initial *labile stage* (M_1) that is subject to cancelation if another saccadic program is subsequently initiated, followed by a *non-labile stage* (M_2) that cannot be cancelled. The times needed to complete both stages are random deviates sampled from gamma distributions with means, respectively, equal to $t(M_1)$ = 125 ms and $t(M_2)$ = 25 ms and *SDs* = 0.22 of those means. For simplicity, the model assumes that a saccade takes 25 ms to execute. During the execution of a saccade, pre-attentive visual processing (which according to the model requires 50 ms to propagate information from the eyes to the systems responsible for lexical processing) halts, but lexical processing continues at a rate determined by the properties of the word currently being processed (as specified by Eqs. 1 and 2) and the distance between the word and the center of vision (Eq. 3). Although saccades are always directed toward the centers of words, the actual length of any given saccade is subject to both random and systematic sources of error (for further discussion, see Reichle, 2011), which results in fixation-location distributions that are approximately Gaussian in shape but with missing "tails" due to saccades that occasionally under/overshoot their intended target. Importantly, whenever the eyes land on a poor viewing location (i.e., near the outer edge of the word instead of its center), an automatic refixation can be initiated to move the eyes closer to the center of the word. The probability, *p*, of initiating a refixation 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 it is modulated by the free parameter λ(= 0.16), as specified by Eq. 4:

$$p = \max(\lambda|fixation - center|, 1) \quad (4)$$

Taken together, the above assumptions can accommodate many of the "benchmark" empirical findings from the literature (for a review, see Rayner, 1998) and has been productively used to examine a variety of theoretical issues related to eye-movement control during reading (for a review, see Reichle, 2011) and non-reading tasks (Reichle et al., 2012). Because the architecture of the model allows for a substantial amount of parafoveal preview, the primary goal of the simulations that are reported below was to determine if the assumptions of the model are sufficient to explain the key findings reported by Reingold et al. (2012). The two simulations reported below thus represent attempts to examine how word frequency, parafoveal preview, and initial fixation location affect the time course of lexical processing and its influence on fixation duration.

3. Simulation 1

Simulation 1 was completed using the standard version of the model (as described above) with all of its default values (see Reichle et al., 2012, Table 1). As such, Simulation 1 provides a very strong test of the model's capacity to simulate the Reingold et al. results and accommodate the severe temporal constraints suggested by those results. As will be discussed below, the model fared reasonably well simulating those results, although there were a number of minor differences between the observed and simulated results.

3.1. Method

The simulations were completed using the lengths, frequencies, and predictabilities of the pre-target and target words used by Reingold et al. (2012) and 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.) The target words were either high frequency (M = 112.1 words per million; Brysbaert & New, 2009) or low frequency (M = 2.5 words per million), the mean lengths of both types of words were 6.5 letters (range = 5–10 characters) and the mean target predictability values were extremely low (high frequency = .013, low frequency = .001). On average, the length, frequency, and predictability values of the pre-target word were 3.8 letters, 18,923 occurrences per million, and 0.17, respectively.

In addition to examining the impact of word frequency (i.e., high vs. low frequency), the simulations examined the impact of the landing position of the first fixation on the target words (i.e., location effects). Similar to Reingold et al. (2012), landing position was determined in the simulations by calculating the proportion of the fixated word to the left of the initial landing position on the word region.[3] To contrast central and outer landing locations, we used Reingold et al.'s formal definition of a "central" location as encompassing all fixations in each condition within a standardized landing position z, such that $-1 < z < 1$. All other fixations (i.e., $z \leq -1$ or $z \geq 1$) were classified as landing on an "outer" location.

Finally, similar to Reingold et al. (2012), the simulations manipulated the availability of parafoveal preview for the target words. In the experiment by Reingold et al., the parafoveal preview manipulation was implemented 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 non-word (i.e., the *invalid* preview condition). To approximate the invalid condition, the simulations adopted the simple assumption that lexical processing does not begin until the eyes fixate on or to the right of the blank space preceding the target word (e.g., see Pollatsek et al., 2006). Although this procedure provides a way of approximating the consequences of preventing parafoveal preview, it is important to note that the procedure is only approximate because there is growing evidence that using letter strings as a mask prior to the boundary change might produce interference (or facilitation) of subsequent processing of the target (e.g., Murray, Rayner, & Wakeford, 2013). That being said, however, our procedure was also necessary because a completely realistic model of the boundary paradigm is likely to entail a precise model of visual and lexical processing, and of how their disruption (in the absence of a correct preview) influences lexical processing after the eyes move across the boundary. Finally, because the E-Z Reader model assumes that lexical processing is the "engine" that moves the eyes forward, a problematic situation can occasionally arise wherein the eyes fall short of the boundary due to saccadic error (i.e., mis-located fixations) and consequently remained indefinitely at that location because there is no signal to move the eyes forward (i.e., because lexical processing of the target word cannot begin). This situation only occurred on a small proportion of trials (fewer than 1%), which were removed from the simulation results reported below. Clearly, further empirical and modeling work is needed to more fully understand the boundary paradigm (for further discussion of these issues, see Schotter, Reichle, & Rayner, 2014; Risse, Hohenstein, Kliegl, & Engbert, 2014).

Thus, Simulation 1 attempted to replicate Reingold et al. (2012)'s empirical findings by manipulating word frequency, initial fixation location, and parafoveal preview in a manner that approximated the empirical manipulations as closely as possible. To provide a strong test of the model, Simulation 1 also examined the model's capacity to simulate these findings using the standard version of the model with all of its default parameter values. We will now report the mean results for Simulation 1, followed by the survival-curve analysis results.

3.2. Results

All the simulation results reported below were obtained by averaging the 1,000 statistical subjects per condition, which provided a reliable estimate of the simulated dependent measures. For all the analyses reported below, we first removed skipped trials[4] (i.e., trials with no first-pass fixations on the target) from the simulated data.

3.2.1. Mean fixation-duration measures

To examine the model's predictions for each of the three manipulations (i.e., word frequency, fixation location, parafoveal preview), we examined the means for the following dependent measures: (a) *first-fixation duration* (i.e., the duration of the first forward fixation on the target, regardless of the number of subsequent fixations on the target); (b) *gaze duration* (i.e., the sum of all the consecutive first-pass fixations on the target, prior to a saccade to another word); (c) *single-fixation duration* (i.e., the first-fixation duration for the subset of trials in which there was only one first-pass fixation on the target); (d) *first-of-multiple fixations* (i.e., the first fixation duration for the subset of trials in which there was more than one first-pass fixation on the target); and (e) *probability of refixation* (i.e., the probability of more than one first-pass fixation on the target).

As can be seen from Figs. 4 and 5, the results from Simulation 1 were largely consistent with the empirical effects of word frequency, fixation location, and parafoveal pre-

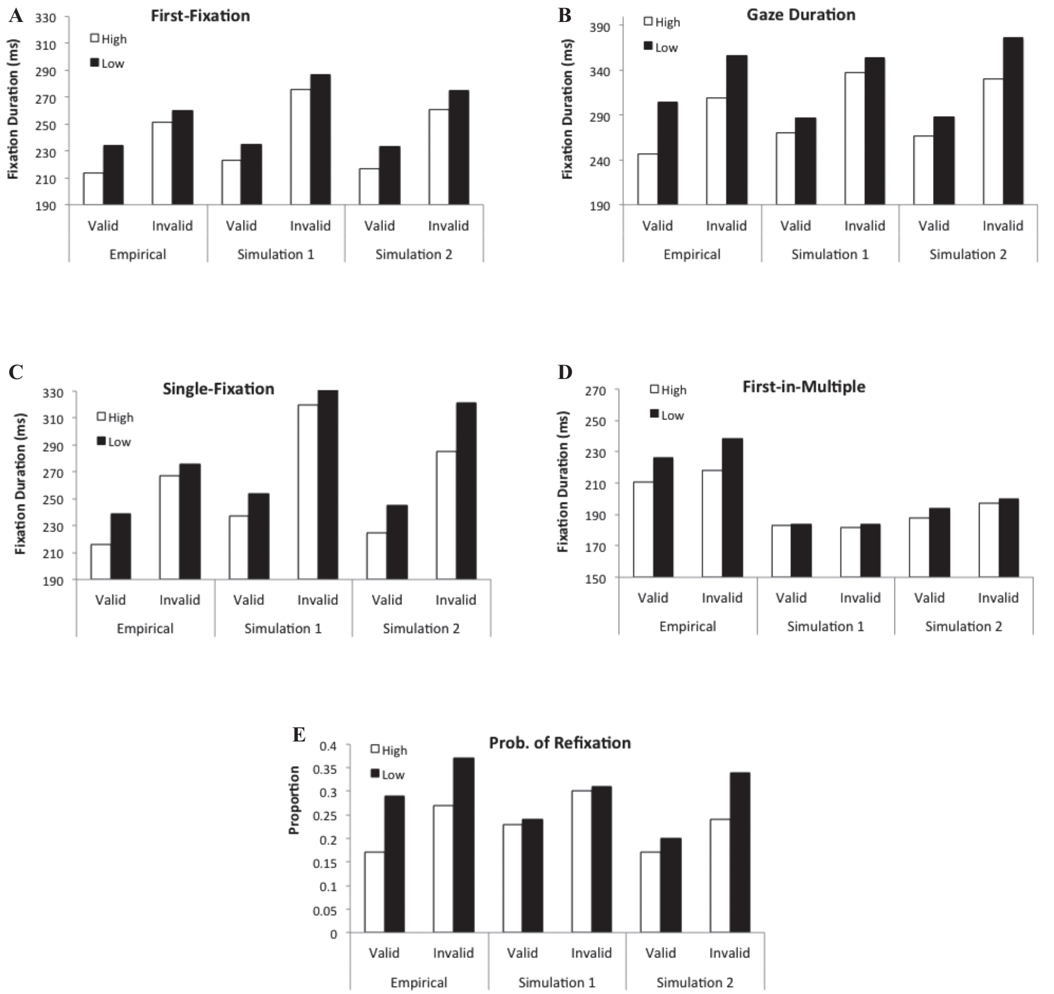

Fig. 4. Observed versus simulated mean fixation-duration measures as a function of word frequency and parafoveal preview. Specifically, the following measures were analyzed (see text for further details): First-Fixation (A), Gaze Duration (B), Single-Fixation (C), First-in-Multiple (D), and Probability of Refixation (E).

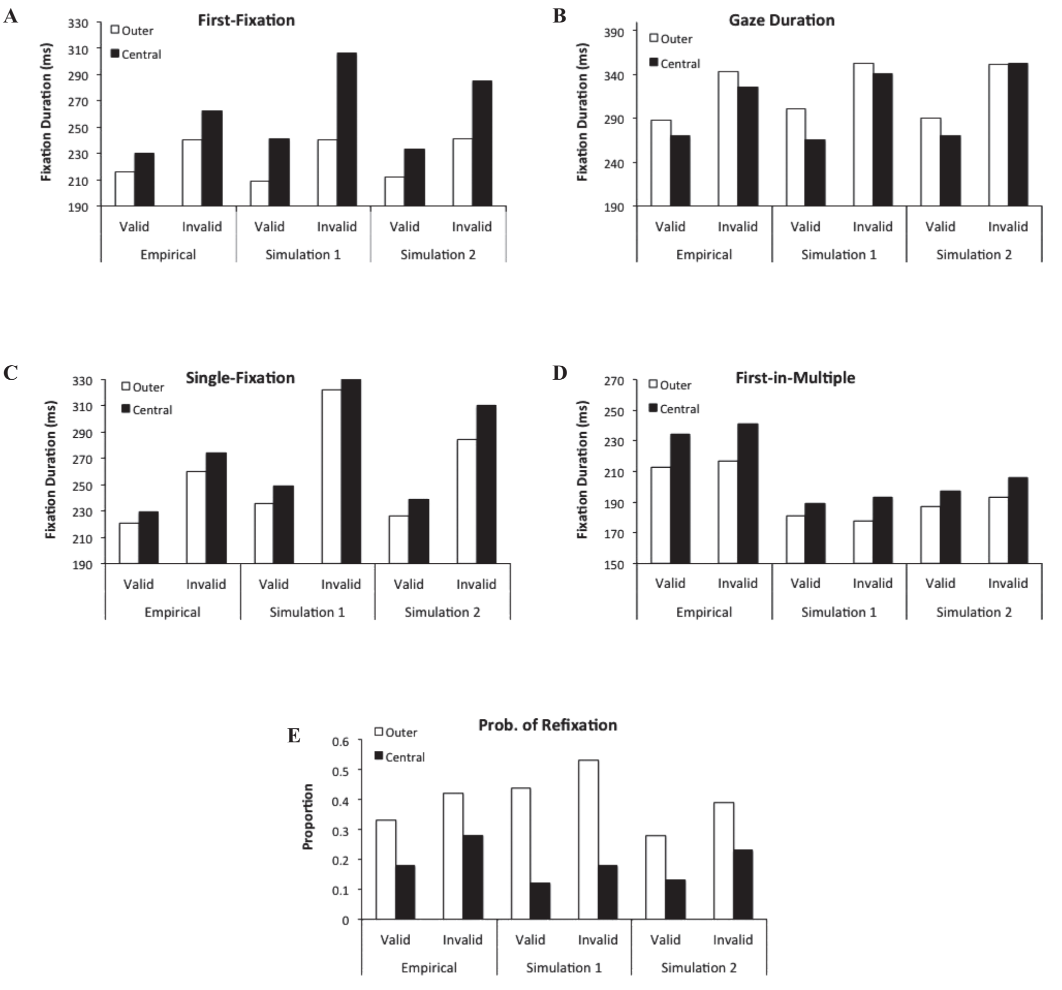

Fig. 5. Observed versus simulated mean fixation-duration measures as a function of fixation location and parafoveal preview. Specifically, the following measures were analyzed (see text for further details): First-Fixation (A), Gaze Duration (B), Single-Fixation (C), First-in-Multiple (D), and Probability of Refixation (E).

view. First, Simulation 1 replicated the empirical word-frequency effects by producing longer fixation times (and higher refixation probabilities) for low- than for high-frequency words (see Fig. 4). Second, Simulation 1 replicated the empirical pattern of fixation-location effects, such that central locations produced longer durations than outer locations for the first-fixation, single fixation, and first-in-multiple fixation measures, whereas the gaze duration measure produced the opposite pattern of results (i.e., longer fixation durations for outer than central locations), with this gaze duration pattern being due to the higher probability of refixation for outer than central locations (see Fig. 5). Finally, Simulation 1 replicated the empirical preview effects, such that fixation times were longer (and refixation probabilities were higher) for the invalid relative to the valid condition.

Although Simulation 1 successfully demonstrated the above main effects of word frequency, fixation location, and parafoveal preview, there were also several notable differences between the simulated and empirical data. In particular, the simulated data tended to over-estimate the duration of single-fixations while simultaneously under-estimating the first-in-multiple durations. This discrepancy in turn meant that the simulated word-frequency effects were too small for the first-in-multiple measure, whereas the simulated fixation-location effects were too large for several of the measures (e.g., first-fixation duration). Given that these discrepancies are more prominent in the invalid than the valid condition, it is possible that the model's implementation of the boundary paradigm is too simplistic, and future work could explore the possibility that the invalid condition produces inhibition of lexical processing (e.g., Murray et al., 2013) rather than simply preventing the initiation of lexical processing (e.g., see Schotter et al., 2014). However, these discrepancies also suggest that the model's assumptions about refixations need to be modified in future versions of the model. To lend support to this conjecture, Simulation 2 (described below) attempted to minimize the aforementioned discrepancies by modifying the model's assumptions about the time course and probability of making refixations.

3.2.2. Survival analyses

As previously discussed, Reingold et al. (2012) used a survival analysis technique to provide fine-grained time-course information about the earliest discernable impact of a variable on first-fixation durations. To illustrate this technique, Fig. 6 displays examples of survival curves that were generated using Reingold et al. (2012)'s empirical data (A and B), and the data from Simulation 1 (C and D). As can be seen from these figures, survival curves are calculated by computing the percentage of "surviving" (i.e., not yet terminated) fixations as a function of time. That is, for each 1-ms time bin t (which varied from 0 to 600 ms), the percentage of first fixations having durations greater than t constituted the percent survival at time t. For both the empirical and the simulated data, the survival curves were calculated separately for each condition and participant and then averaged across participants.

Importantly, by examining the survival curves in Fig. 6, it is possible to see that the curves for each of the two values of the manipulated variables appear to diverge. More specifically, the curves for low-frequency target words begin to decrease at a slower rate than the curves for high-frequency target words (see A and C), and the curves for central fixation locations begin to decrease at a slower rate than those for outer fixation locations (see B and D). Reingold et al. (2012) identified the earliest point in time at which the survival curves across two conditions first begin to significantly diverge (henceforth referred to as the *divergence point*), and they argued that this divergence point provides an estimate of the earliest discernable influence of a variable on fixation durations. To calculate the divergence point using their empirical data, Reingold et al. used a bootstrap resampling procedure (Efron & Tibshirani, 1994) that was designed to provide an estimate of the earliest 1-ms time bin that showed a statistically reliable difference across conditions (for further discussion of this approach, see Reingold et al., 2012; Reingold & Sheridan, 2014).

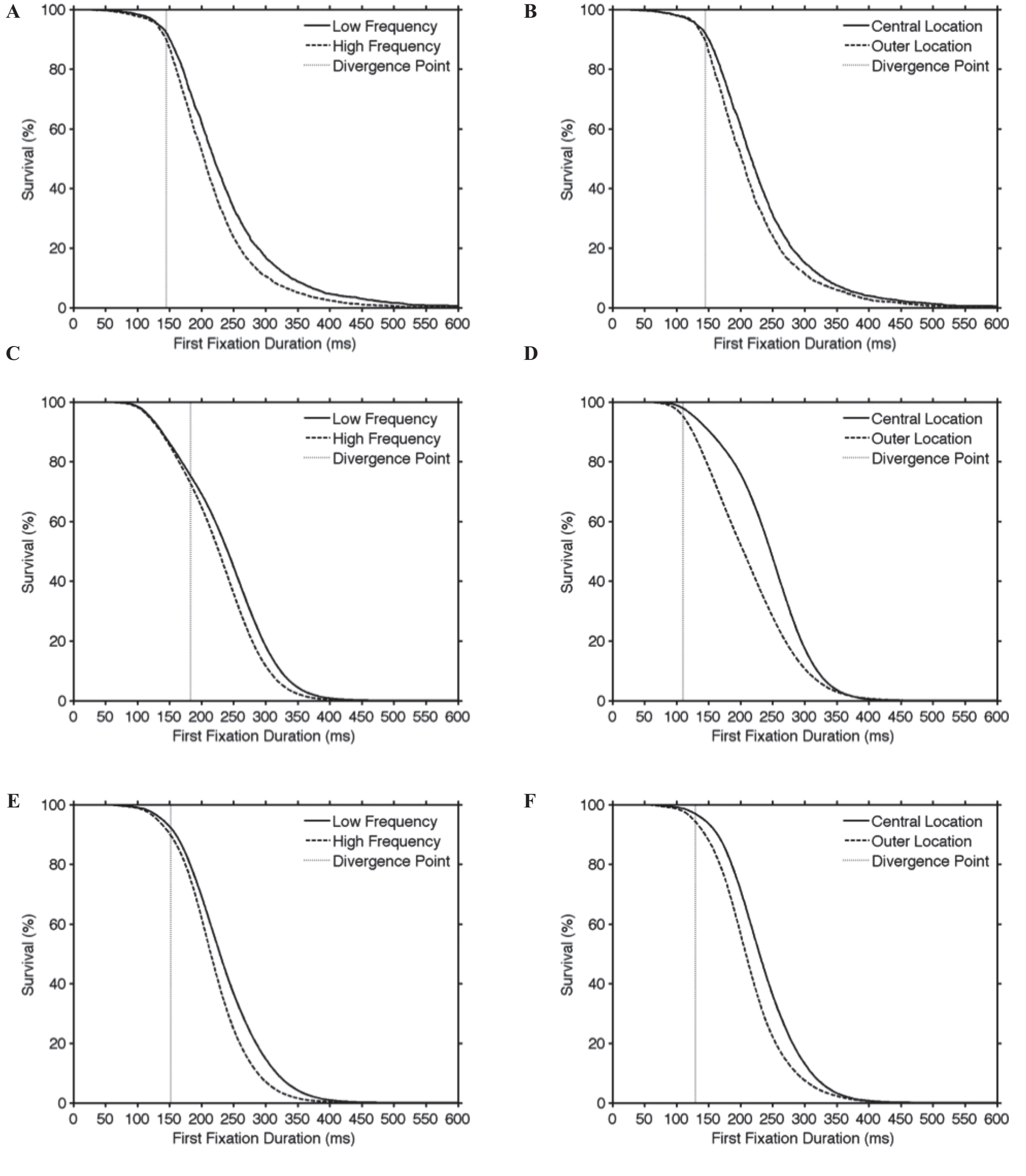

Fig. 6. Observed versus simulated survival curves under normal reading conditions (i.e., valid preview), as a function of word frequency (see A, C, and E) and fixation location (see B, D, and F), from the experiment reported by Reingold et al. (2012) (A and B), Simulation 1 (C and D), and Simulation 2 (E and F). The vertical dotted lines indicate the divergence points (see text for details).

In the present simulations, our goal was to directly compare the empirically obtained divergence points with time-course estimates derived from the simulated data. Accordingly, for each of the divergence points shown in Table 1, we used the empirical datasets from

Table 1
Survival-curve divergence points (in ms) as a function of word frequency, parafoveal preview, and fixation location from the experiment reported by Reingold et al. (2012) and from two simulations using E-Z Reader

Independent Variables	Empirical	Simulation 1	Simulation 2
Word frequency × Preview			
Valid preview	145	183	152
Invalid preview	256	281	259
Word frequency × Location			
Central location	163	208	206
Outer location	256	319	266
Location × Preview			
Valid preview	145	110	129
Invalid preview	142	105	123
Location × Frequency			
High frequency	141	108	129
Low frequency	144	105	124

Note. Simulation 1 used the standard version of E-Z Reader with its default parameter values (Reichle et al., 2012); Simulation 2 used the modified version of the model (cf., Eqs. 4 vs. 5) and best-fitting values of α_1 and α_2.

Reingold et al. (2012) to calculate the size of the difference between the survival curves at the obtained point of divergence (i.e., at the point of divergence, we subtracted the mean survival rate in the faster condition from the mean survival rate in the slower condition), to obtain a "difference criterion" that ranged in magnitude from 1.5% to 4% across the empirical divergence point analyses reported in Table 1. We then defined the simulated divergence points to be the earliest 1-ms time bin that showed a difference across conditions that was equal in magnitude to (or greater than) the difference criterion from the corresponding empirical analysis. This procedure allowed us to derive predicted divergence points from the simulated data, which could then be compared with the original divergence points from the empirical data. Both the empirical and simulated divergence points are shown as vertical dotted lines for the example survival curves shown in Fig. 6, and Table 1 summarizes all the divergence points obtained from the empirical and simulated datasets.

As can be seen from Table 1, the survival analysis results from Simulation 1 showed a qualitatively similar pattern of results to the empirical survival analyses. Most important, for both the simulated and empirical datasets, the word-frequency variable had a rapid effect on the distributions for normal reading (i.e., valid preview) and this effect was substantially delayed in the invalid preview condition. Specifically, in Simulation 1, the word-frequency divergence points were 183 ms in the valid condition and 281 ms in the invalid condition (i.e., a difference of 98 ms), whereas for the empirical dataset the corresponding valid and invalid divergence points were 145 and 256 ms (i.e., a difference of 111 ms). Thus, although the simulated divergence points were slightly delayed relative to what was observed, the simulated results nonetheless strongly supported Reingold et al. (2012)'s main conclusion that word frequency has a rapid effect on fixations under normal reading conditions, and that such rapid lexical effects are supported by a substantial amount of parafoveal processing.

In addition to examining the time course of word-frequency effects as a function of parafoveal preview, we also examined word-frequency effects for central versus outer fixation locations. As can be seen from Table 1, the model successfully predicted earlier word-frequency effects for central relative to outer fixation locations (i.e., central = 208 ms vs. outer = 319 ms), which is consistent with the empirical results (i.e., central = 163 ms vs. outer = 256 ms). Although the simulated divergence points again occurred slightly later than the empirical divergence points, Simulation 1 replicated the empirical finding that lexical processing is faster for central than outer fixation locations. This lexical processing benefit for central locations is likely due to the drop-offs in visual acuity that occur when the eyes land farther away from the center of a word (for further discussion, see Kliegl et al., 2006; Nuthmann et al., 2005, 2007; Vitu et al., 2007, 2001).

Finally, as can be seen from Table 1, Simulation 1 also correctly predicted that location divergence points would be equally rapid regardless of preview (i.e., valid vs. invalid) and regardless of target-word frequency (i.e., high vs. low). This pattern of results supports Reingold et al. (2012)'s conclusions that, unlike word-frequency effects, location effects are driven by non-lexical factors that do not produce time-course differences across conditions. However, it is important to note that, although the simulated location divergence points replicated the qualitative pattern of empirical results, the model predicted an earlier effect of location in Simulation 1 (range = 105–110 ms), relative to the empirical location divergence points (range = 141–145 ms). This tendency of the model to predict earlier fixation-location effects than what was observed is consistent with the simulated means reported earlier, indicating that the model over-estimates the size of location effects.

3.3. Interim summary

Overall, Simulation 1 demonstrated that the E-Z Reader model's predictions about the influence of word frequency, initial fixation location, and parafoveal preview on fixation durations were qualitatively similar to the empirical observations reported by Reingold et al. (2012). In addition to successfully predicting mean effects for the manipulations of all three variables, the model also approximated the empirical findings of rapid word frequency and location effects, in combination with the finding that word-frequency effects (but not location effects) were dramatically delayed under invalid relative to valid preview conditions. It is also important to note that the model accommodated this complex pattern of results despite the fact that the model was not originally designed to explain time-course results like those reported by Reingold et al., and despite the fact that Simulation 1 used all the model's default parameter values.

However, it is also important to note that, although the model could account for Reingold et al. (2012)'s main pattern of results, there were nonetheless some minor discrepancies between the simulated and empirical results. These discrepancies suggest that the model's assumptions about refixations are not quite accurate. For example, relative to the empirical data, the simulated survival analysis produced numerically delayed word-frequency divergence points and numerically earlier fixation-location divergence points. Simulation 2 addresses these discrepancies with the goal of providing an even better fit between the empirical and simulated data.

4. Simulation 2

Building on Simulation 1, which demonstrated that the default version of the E-Z Reader model can largely accommodate the main findings from Reingold et al. (2012), Simulation 2 explored several modifications to the model's default assumptions and parameters, with the goal of further improving the fit between the simulated and empirical data. Specifically, as will be discussed in detail below, we adjusted the parameters that control the rate of lexical processing in the model and modified the model's assumptions about the probability of initiating and timing of refixations. As will become evident below, these two changes were effective at reducing the minor discrepancies that were observed between the empirical and simulated results in Simulation 1.

4.1. Method

The method used was identical to that of Simulation 1 (see description above), except for four modifications. The first two were both related to the model's default parameter values. First, the value of the parameter controlling the overall rate of lexical processing (i.e., α_1; see Eq. 1) was reduced from its default value (i.e., 104) to 100, thereby increasing (slightly) the overall rate of lexical processing. Second, the value of the parameter controlling how word frequency modulates lexical processing (i.e., α_2) was increased from its default value (i.e., 3.5) to 6.5, thereby increasing the degree to which word frequency modulates the rate of lexical processing. Both these changes were motivated by Simulation 1, which showed that the model's default parameters tended to under-predict the degree to which word frequency modulated the first-of-multiple fixation durations. These changes were also motivated—as indicated in our earlier exposition of the E-Z Reader model—by a considerable amount of previous work showing that the values of these parameters appear to be related to differences in reading ability and text materials (Mancheva et al., 2014; Rayner et al., 2006; Reichle et al., 2013; see also, e.g., Miellet, Sparrow, & Sereno, 2007). And it is also worth emphasizing that neither parameter adjustment weakens the model's core assumption that attention is allocated in a strictly serial manner—that assumption is completely determined by the model's architecture (i.e., how information and control of processing is passed between the L_1, L_2, and A components in Fig. 3).

The next two modifications were both related to the model's assumptions about refixations. First, a 50-ms delay (corresponding to the duration of the eye-brain lag; i.e., $V = 50$ ms) was introduced prior to the initiation of refixations. Second, the free parameter λ (see Eq. 4) with its default value of 0.16 was replaced by two parameters (see

Eq. 5)—the first controlling the overall propensity to make a refixation (i.e., $\lambda_1 = 0.20$), and the second controlling how this propensity to refixate is modulated by saccadic error (i.e., $\lambda_2 = 0.20$). The intuitions behind these two changes are simply that the "decision" to refixate a word is not immediate (i.e., it is delayed by 50 ms) and occurs with some non-zero probability. In contrast, the standard version of E-Z Reader assumes that the programming of refixations is initiated immediately after a word is fixated, using efference copy information (Carpenter, 2000) that is immediately available to the oculomotor system about the location of the initial fixation relative to the intended saccade target (i.e., the center of the word being fixated). Simulation 2 thus explores the alternative assumption that this feedback about saccadic error is based on visual information, thereby necessitating some minimal amount of time (i.e., 50 ms) prior to the initiation of a refixation program.

$$p = \max[\lambda_1 + \lambda_2|\mathit{fixation} - \mathit{center}|, 1] \quad (5)$$

The best-fitting parameter values that were used in Simulation 2 were found by completing grid searches of a parameter space defined by four parameters: (a) α_1; (b) α_2; (c) λ_1; and (d) λ_2. Specifically, simulations were performed by systematically incrementing the values of these four parameters and then using each possible permutation of those values to examine how they affected the model's performance as measured using the *root-mean-squared deviation* (*RMSD*) between the mean observed and simulated values for each of the following dependent measures: (a) first-fixation durations; (b) gaze durations; (c) single-fixation durations; (d) first-of-multiple fixation durations; (e) the probabilities of fixating once; and (f) the probabilities of skipping. For further details about this procedure, see the Appendix of Reichle et al. (1998).

4.2. Results

4.2.1. Mean fixation-duration measures

Similar to Simulation 1, Simulation 2 successfully accommodated the empirical findings concerning word frequency, fixation location, and parafoveal preview (see Figs. 4 and 5). However, in contrast to Simulation 1, which over-predicted single-fixation durations while simultaneously under-predicting the first-in-multiple fixation durations, Simulation 2 predicted fixation durations that were more in line with those observed. Moreover, the size of the word-frequency effects for the first-in-multiple measure was larger for Simulation 2 than Simulation 1, which is also more in line with the empirical data. Finally, Simulation 2 predicted smaller fixation-location effects than Simulation 1, which is also more in line with the empirical data (although these effects were still too large in the invalid preview condition). Thus, for the analyses of the mean fixation-duration measures, Simulation 2 provided an even better fit to the empirical data than Simulation 1, suggesting that the assumptions about refixations that were used in Simulation 2 may provide a better approximation to reality than those of the standard model.

4.2.2. Survival analyses

As can be seen from Table 1 and Fig. 6E and F, Simulation 2 can explain all the survival analysis findings that were accommodated by Simulation 1, while also providing an even closer fit to the empirical data than Simulation 1. In particular, Simulation 2's word-frequency divergence points were 152 ms in the valid condition and 259 ms in the invalid condition (i.e., a difference of 107 ms), which is very similar to the corresponding empirical divergence points of 145 and 256 ms (i.e., a difference of 111 ms). Word-frequency effects were also delayed for outer relative to central landing locations, both for Simulation 2 (i.e., central = 206 ms vs. outer = 266 ms) and the empirical results (i.e., central = 163 ms vs. outer = 256 ms). In contrast, the fixation-location effects were equally rapid regardless of word frequency and preview, both for Simulation 2 (range = 123–129) and the empirical data (range = 141–145 ms).

4.3. Interim summary

With the exception of some minor residual differences (e.g., fixation-location effects occurred slightly earlier for the simulated relative to the empirical data), Simulation 2 provided an even better approximation of the empirical results than Simulation 1, which suggests that the modified parameter values and refixation assumptions used in Simulation 2 are a promising direction for future modeling efforts. Moreover, taken together, Simulations 1 and 2 support Reingold et al. (2012)'s main conclusion that rapidly emerging word-frequency effects are enabled by a substantial amount of parafoveal preview, whereas fixation-location effects emerge equally rapidly irrespective of both parafoveal preview and word frequency.

5. General discussion

As we indicated at the beginning of this article, our primary goal in completing the simulations reported herein was to evaluate whether or not the assumption of serial-attention allocation was plausible given the severe temporal constraints that have been shown to exist because of the times that are required to engage in lexical processing and to program saccades. As Reichle and Reingold (2013)'s review of the physiological "markers" of lexical processing indicate, and consistent with the conclusions drawn from the survival-curve analyses reported by Reingold et al. (2012), the amount of time required to complete both lexical processing and saccadic programming necessitates a significant amount of parafoveal lexical processing. As Fig. 2B illustrates, the assumption that parafoveal processing plays a significant functional role during normal reading provides a means of explaining how something as sluggish as lexical processing can mediate the decisions about when to move the eyes from one word to the next. What was less clear, however, was the question of whether or not this assumption of significant parafoveal processing was congruent with the theoretical assumptions of serial-attention models of eye-movement control in reading (e.g., see Reichle, 2011). Our simulations using E-Z Reader directly address this question by demonstrating how a model that posits the strictly serial allocation of attention is consistent with the experimental findings reported by Reingold et al.

Most important, the model replicated the finding that word frequency has a very rapid effect on fixation durations during normal preview. For example, as Table 1 shows, in Simulation 2, the survival curves for fixation durations on high- versus low-frequency words began to diverge 152 ms after the start of the fixations on the target words, as compared to the divergence point of 145 ms reported by Reingold et al. (2012). Similarly, the model replicated the substantial slowing down of lexical processing that was evident in the invalid preview condition. For example, in Simulation 2, without parafoveal preview, the survival curves for fixation durations on high- and low-frequency targets began to diverge at 259 ms post-fixation onset, as compared to the observed divergence point of 256 ms. Together, these two simulation results indicate that, in the simulation of Reingold et al.'s experiment, the model engaged in a significant amount of parafoveal lexical processing—approximately 107 ms (i.e., 259–152 ms). This value is remarkably close to the 111 ms estimate that was reported by Reingold et al., and as such is consistent with the interpretation that those authors provided of their results *and* the hypothesis that direct lexical control of eye movements during reading is possible because of the fact that a considerable amount of lexical processing is completed from the parafovea, prior to words actually being fixated.

As Table 1 also shows, the model accurately replicated the key findings related to fixation location. For example, the divergence point for word frequency in Simulation 2 occurred earlier for central (206 ms) as compared to outer (266 ms) fixations. However, the effect of fixation location was not modulated by parafoveal preview or word frequency. For example, in Simulation 2, the survival curves for fixation durations on central versus outer locations began to diverge at 129 ms in the valid preview condition and at 123 ms in the invalid preview condition. Similarly, the survival curves for fixation durations on central versus outer locations began to diverge at 129 ms for high-frequency target words and at 124 ms for low-frequency target words. All these simulated divergence points correspond fairly closely with the values reported by Reingold et al. (2012) and are thus consistent with their suggestion that non-lexical variables (e.g., fixation location) can also rapidly influence decisions about when to move the eyes during reading. Importantly, the simulations demonstrate how both lexical and non-lexical control can interact within the framework of E-Z Reader to jointly determine when and where the eyes move during reading. As such, the simulations provide proof that the severe temporal constraints on lexical processing and saccadic programming (as reviewed by Reichle & Reingold, 2013) are not necessarily incompatible with the theoretical assumption that, during reading, words are attended, processed, and identified one at a time, in a strictly serial manner.

Finally, it is important to note that the model also replicated the main effects of the three variables of interest in the Reingold et al. (2012) experiment—word frequency, initial fixation location, and parafoveal preview. This claim is best appreciated if one inspects Figs. 4 and 5, which show how these three variables affected the mean values for five different dependent measures. As the figures show, in most instances the correspondences between the observed and simulated means are fairly close, especially if one considers the results of Simulation 2. For example, in that simulation, all four of the means defined by the factorial combination of word frequency and preview are within 15 ms of their observed values for first-fixation durations, within 21 ms of their observed values for gaze durations, and exhibit frequency and preview effects of the correct magnitude. Similarly, all four of the means defined by the factorial combination of word frequency and fixation location are within 23 ms for first-fixation durations, 27 ms for gaze durations, and exhibit frequency and fixation-location effects of the correct magnitude. However, careful inspection of the figures also suggests that the model is less successful at explaining refixations, and even in Simulation 2 (which was motivated by these discrepancies), the model has difficulty accounting for the precise relationship between each of the three variables of interest and single-fixation durations, the durations of the first-of-multiple fixations, and the probabilities of making refixations.

For example, as Figs. 4 and 5 show, the model exhibits a clear tendency to over-estimate the durations of single fixations while it simultaneously under-estimates the durations of first-of-multiple fixations. Although this tendency was reduced in Simulation 2 by introducing the assumptions that refixations are initiated with some non-zero probability on the basis of visual feedback about the amount of saccadic error, the fact that this problem persists suggests that the model's assumptions about refixations are still not completely accurate. This inaccuracy may reflect the fact that there may be multiple mechanisms that actually produce refixations in human readers (e.g., the simultaneous programming of saccades to move the eyes in quick succession to two different viewing positions within a given word; Vergilino & Beauvillain, 2000) that are not captured by the model's relatively simple assumptions. Or alternatively, the manner in which the invalid preview condition was implemented in our simulations (i.e., by simply preventing the initiation of lexical processing until the model's "eyes" crossed the blank space preceding the target words) may not accurately reflect the inherent complexity that is associated with processing non-word previews (Schotter et al., 2014). For example, there is some evidence that, rather than simply delaying the start of lexical processing, the presence of non-word previews actually somehow inhibits lexical processing of a target word when it is eventually fixated (e.g., see Murray et al., 2013). Either or both types of inaccuracy may have contributed to the discrepancies that are evident between the observed and simulated means in the measures that are most sensitive to refixations, and as such, it will be important to examine both these issues more carefully in future experiments and simulations.

Finally, it is important to emphasize that the types of simulations reported in this article represent a step toward the use of more complex patterns of data (i.e., patterns other than simple means) to evaluate the theoretical assumptions of eye-movement control models. We believe that this step is and will continue to be critical in the further development of the field and—in particular—the development and refinement of eye-movement models. The reason why we hold this belief is that, during the last decade, a number of these models have already been shown to be sufficient to explain existing "benchmark" findings related to eye movements in reading. For example, currently the E-Z Reader model (Reichle et al., 2012), SWIFT (Engbert et al., 2005), and SERIF (McDonald et al., 2005) provide detailed accounts of word-frequency effects in reading and quantitative fits of data that have reported word-frequency effects (e.g., the effects observed in the Schilling et al., 1998 sentence corpus). Although the capacity to accurately simulate such effects is on some level a significant accomplishment, it also indicates that such effects can be explained using very different theoretical assumptions that —when used to explain the differences among mean fixation durations on words having different frequencies—fare about equally well.

With the recent application of methods to analyzing distributions, however, "the bar has been raised" with respect to the types of data that the models must now explain. For example, several studies using ex-Gaussian analyses to determine how fixation-duration distributions change as a function of some variable of interest (e.g., word frequency) have provided important new information that any viable model of eye-movement control must explain—that differences in word frequency cause a shift in the underlying mean of fixation-duration distributions, thus indicating that both short and long fixations were impacted by the manipulation (for further discussion, see Staub et al., 2010). On some level this should not be surprising because distributions of variables provide more information about those variables than do their means. In the context of the present simulations, for example, the method of identifying points of divergence between two or more survival curves provides fine-grained information about when a variable (e.g., word frequency) first has a discernable effect. This, in turn, has proven extremely informative because it suggests that, without some significant amount of parafoveal lexical processing, the lexical processing of a word that happens while the word is being fixated is not sufficiently rapid to allow direct (lexical) control of eye movements during reading. The simple fact that a strictly serial-attention model like E-Z Reader can accommodate these findings represents a significant success of the model; this success was not predicted nor guaranteed a priori, and as such, provides additional new support for the theoretical assumptions of the model.

That being said, although the temporal constraints that were discussed in the beginning of this article (see Fig. 2) are most obviously pertinent to the theoretical assumption that words are processed in a serial manner (because of the inherent restrictions associated with this assumption), it is worth emphasizing that the temporal constraints are equally pertinent to parallel-attention models like SWIFT (Engbert et al., 2005) and Glenmore (Reilly & Radach, 2006). The reason why this is true can be most readily appreciated by considering the pattern of results reported by Reingold et al. (2012) and simulated in this article: To adequately explain these results, a model of eye-movement control during reading must simultaneously explain how target-word frequency, the presence versus absence of parafoveal preview, and initial fixation location influence various mean measures of looking time on those target words, and when those variables first exert an influence on the distributions of fixation durations on those words. Rephrasing this problem a bit more intuitively: Any viable model of eye-movement control has to explain how lexical processing influences the decisions about when to move the eyes off of a word, and how these decisions are in turn influenced by parafoveal processing and where the eyes actually move. Of course, such an account also has be consistent with other basic effects that are often not the focus of research articles because of their obvious nature—such as the fact that participants in boundary-paradigm experiments only occasionally notice the display changes that occur as their eyes move onto the target words. Thus, any viable parallel-attention model would have to simultaneously explain how enough parafoveal lexical processing happens to mediate direct lexical control over the decisions about when to move the eyes, but not so much parafoveal processing that it would presumably allow (conscious) awareness of the display changes, nor so little parafoveal processing that the model effectively becomes a serial-attention model.

In summary, we believe that the recent use of experimental methods that allow for more careful examination of how variables of interest influence fixation-duration distributions represents real progress in the study of eye-movement control during reading—progress that is consistent with recent work in other domains of cognitive research (e.g., reaction time distributions in visual-search tasks; Palmer, Horowitz, Torralba, & Wolfe, 2011). As demonstrated in this article, the findings from experiments using these new methods are playing (and will increasingly play) critical roles in the evaluation and development of computational models of eye-movement control in reading. That being said, we believe that the specific pattern of results reported by Reingold et al. (2012) represent important empirical benchmark findings that any viable model should be able to explain.

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Notes

1. These markers are inherently conservative because they represent the earliest statistically significant evidence for lexical processing; as such, it is reasonable to assume that such processing might begin even earlier than the estimates suggest.
2. For reviews of these eye-movement control models, see Reichle, Rayner, and Pollatsek (2003) or the 2006 special issue of *Cognitive Systems Research*.
3. Note that for each target word, Reingold et al. (2012) defined a word region as extending from the middle of the space preceding the word to the middle of the space following the word. However, for simulations using E-Z Reader, the target-

word region was defined as the region extending from the beginning of the space preceding the target word to the beginning of the space following the word. This minor methodological difference was necessary to make the simulations compatible with previously reported simulations and was deemed unimportant because our goal was to examine the effect of outer versus central rather than absolute fixation location.

4. The mean proportion of skipped target words in the valid (i.e., normal reading) condition was .03 for Simulation 1, .10 for Simulation 2, and .08 for the empirical data. The corresponding skipping rates for the invalid condition were .02 for Simulation 1, .05 for Simulation 2, and .07 for the empirical data.

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