

# *E–Z* Reader: A cognitive-control, serial-attention model of eye-movement behavior during reading ☆

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## Abstract

The two core assumptions of the *E–Z* Reader model of eye-movement control during reading are that: (1) a preliminary stage of lexical access (i.e., the familiarity check) triggers the initiation of a saccadic program to move the eyes from one word to the next; and (2) attention is allocated serially, to one word at a time. This paper provides an overview of the model, some of the research that motivated its assumptions, and the various reading-related phenomena that the model can account for. This paper also summarizes how the model has been and is currently being used to guide empirical research.

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## 1. Introduction

The *E–Z* Reader model belongs to the class of reading models called *cognitive-control* models because it posits a fairly tight link between the mind and eyes during reading. There are two core assumptions of *E–Z* Reader that endow it with this property and also make it unique among the models that are described in this volume. The first is that attention is allocated in a strictly serial fashion – to only one word at a time. The second is that processes involved in the encoding of the attended word are the signals for both saccadic programming and for a shift of covert attention. However, saccadic programming is decoupled from attention; the signal for the oculomotor system to start programming a saccade to the next word is the completion of

an early stage of lexical processing, whereas the signal for spatial attention to shift to the next word is completion of lexical access. As we have argued elsewhere (Rayner, Pollatsek, & Reichle, 2003), we believe that both of the model's core assumptions are well founded, being based upon and consistent with a considerable amount of empirical evidence. And perhaps more importantly, we believe that the model provides a fairly simple and conceptually transparent account for how the cognitive processes that mediate attention, lexical processing, and – to a more limited extent – higher-level language processing, determine when and where the eyes move during reading. We therefore contend that our model is the most complete and accurate account of eye-movement control during reading. Our goals in the remainder of this article will be to first support this assertion, and then to demonstrate why our model is a useful heuristic for understanding the “eye-mind” link in reading and – on a much more general level – for understanding a variety of issues pertinent to the psychology of reading.

To meet our goals, we will first describe our model and give some preliminary justification for its assumptions. We

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will then describe the results of several simulations that show how the model is able to account for a variety of “benchmark” phenomena that one might expect any viable model of eye-movement control to explain. (These phenomena – except where otherwise noted – are well documented and relatively uncontroversial; for a recent review of these phenomena, see Rayner, 1998). We will also briefly describe the results of two new simulations of experiments that have used *gaze-contingent display-change paradigms* (i.e., paradigms in which what is displayed upon the computer screen is contingent upon where the participant is looking). We believe that these paradigms are especially informative because they impose fairly tight constraints on the time-course of visual and lexical processing during reading. For this reason, we also believe that explaining the results of these paradigms will prove to be problematic for the alternative models of eye-movement control that are discussed in this special issue. Finally, we will close this article with a discussion of several new lines of research that have been motivated by our model; this research is encouraging because it provides additional support for the basic assumptions of our model.

## 2. *E-Z* Reader: An overview of its assumptions and their motivation

As already mentioned, the first core assumption of the *E-Z* Reader model<sup>1</sup> is that attention is allocated serially, to one word at a time. A corollary of this assumption is that attention is intrinsically linked to lexical processing. In other words, the visual processing that is necessary for lexical processing is not sufficient to support word identification; word identification also requires that attention be focused on the word that is being processed. This assumption is based on a considerable amount of evidence that attention is necessary to “bind” together the features of visual “objects” so that they can be encoded as single, unified representations (Pollatsek & Digman, 1977; Treisman & Gelade, 1980; Treisman & Souther, 1986; Wheeler & Treisman, 2002; Wolfe, 1994; Wolfe & Bennett, 1996). This literature has provided evidence that, without attention, the features from even relatively simple visual arrays (e.g., red T’s and green F’s) are likely to be mis-parsed, resulting in illusory conjunctions and the perception of objects that are not actually in the stimulus array (e.g., a red F). If one grants that it is more difficult to identify words than it is to identify single letters, then our assumption that

attention must be allocated to each word “object” so that it can be identified is not unreasonable. In our model, lexical processing begins as soon as attention is focused on a word’s visual features. This allows the features of the word to be bound together into a single “object” so that the systems that are responsible for lexical processing can begin computing the word’s orthographic, phonological, and semantic codes.

Another benefit that may come from allocating attention serially is that it provides a simple mechanism for encoding the order of the words that are being read (Pollatsek & Rayner, 1999). This is advantageous in languages such as English in which word order conveys a large amount of syntactic information (e.g., “run home” vs. “home run”). Even in highly inflected languages (e.g., German), in which much of the syntactic information is explicitly represented through case markings, nuances in meaning are none-the-less often conveyed through word order. For example, in Finnish, a highly inflected language, word order conveys information about discourse status (Vallduvi & Engdahl, 1996). Similarly, word order in Hungarian and Turkish (also both highly inflected languages) conveys information about topic focus and given-new status (Kaiser & Trueswell, 2004).

This distinction between an early stage of pre-attentive visual processing and a subsequent stage of attention-based lexical processing was also motivated by our appreciation of the fact that the information on the retina is not transmitted instantaneously to the brain, but instead lags behind by some amount of time. Several recent experiments using physiological methods have given consistent estimates of the duration of the “eye-to-brain” lag: approximately 50 ms (Clark, Fan, & Hillard, 1995; Foxe & Simpson, 2002; Mouchetant-Rostaing, Giard, Bentin, Aguera, & Pernier, 2000; Van Rullen & Thorpe, 2001). We have consequently adopted this estimate in our modeling; in *E-Z* Reader, the time that is needed to propagate visual information from the eye to the brain is fixed equal to 50 ms. We further assume that whatever visual information is gleaned from one viewing location will continue to be used by the cognitive systems until new information from the next viewing location becomes available. Although our reasons for making this assumption are beyond the scope of this paper (see Pollatsek et al., 2005), the consequence of this assumption is that the eye-to-mind lag will be essentially invisible except in situations involving very large saccades (e.g., long regressions, which are outside of the scope of our model). However, one exception to this is that any change in visual acuity that results from moving the eyes to a new viewing location will not be immediate, but will instead be delayed by 50 ms. This assumption will have consequences for display-change paradigms, which we will discuss later.

Because this early visual processing is not dependent upon attention, some information from across the entire visual field is processed from each new fixation. This means that low-level visual information from the entire page will be processed in parallel (subject to limitations in visual

<sup>1</sup> The model that is described in this paper is actually one of a family of models that we have continued to refine so as to make the model both more plausible (e.g., more realistic parameter estimates) and more comprehensive in its theoretical scope (e.g., able to account for more phenomena). We therefore refer to the current version of our model as *E-Z* Reader 9 (for descriptions of earlier versions of our model, see Reichle, Pollatsek, Fisher, & Rayner, 1998; Reichle, Rayner, & Pollatsek, 1999, 2003). For an in-depth discussion of the theoretical issues that motivated the development of *E-Z* Reader 9, see Pollatsek, Reichle, and Rayner (2005).

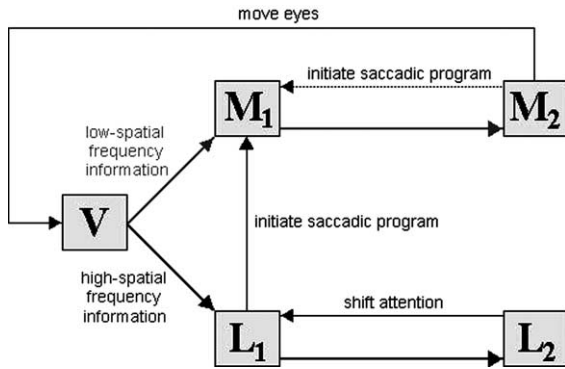


Fig. 1. Schematic diagram of the E-Z Reader model of eye-movement control during reading.

acuity, of course). This assumption is important because, even though visual acuity drops off quite rapidly from the center of vision (i.e., the fixation location), the low-spatial frequency information that is available from parafoveal and peripheral vision provides information about word length and shape, and the boundaries between words. Although peripheral information is occasionally used, such as the information about where the left boundary of text is to guide “return sweeps” (large saccades to the beginning of the next line of text), in general, the visual information that is actually used in reading is within a relatively narrow window in which word and letter identification is actually occurring: from about four letters to the left of fixation to about 14–15 letters to the right of fixation on the line of text being read (McConkie & Rayner, 1975; Rayner & Bertera, 1979; Rayner, McConkie, & Zola, 1980). In our model, we assume that this information can be used by the oculomotor system to select saccade targets. (This is shown in Fig. 1, which is a schematic diagram of the model.) The assumption that low-level featural information is processed in parallel also suggests an explanation for why unusual letter sequences at the beginning of a word can affect fixation durations on the prior word (Inhoff, Radach, Eiter, & Juhasz, 2003); because these letter sequences are unusual, they may contain unusual features that “pop out” of the visual field, drawing attention to themselves and hence being rapidly noticed by the reader.<sup>2</sup> By this account, such low-level

<sup>2</sup> As one reviewer correctly noted, it is not clear if such pop-out effects (which occur with low-level visual features; e.g., oriented line segments; Pashler, 1998) generalize to more complex, learned patterns (e.g., letter sequences). Although the evidence for these types of pop-out effects is equivocal (see Pashler, 1998), there is evidence that lower-level visual features can be processed in parallel, across two or more words. White (2005) showed that *orthographic familiarity*, or how frequently a word’s sub-word letter sequences occur in printed text, can produce parafoveal-on-fovea effects. In White’s experiment, the familiarity of word  $n$ ’s letter sequences modulated fixation durations on word  $n$  and word  $n - 1$ . However, the frequency of word  $n$  only modulated the fixation duration on word  $n$ , and not word  $n - 1$ . Together, these findings are consistent with our claim that – in contrast to lexical processing – an early stage of pre-lexical (orthographic) processing is being completed in parallel on two or more words.

parafoveal-on-foveal effects are not damning to our assumption that attention is allocated in a strictly serial manner because such effects do not require attention – they are pre-attentive.

As already stated, lexical processing of a word is assumed to begin as soon as attention is allocated to the visual features of that word. In our model, we have assumed that lexical processing is completed in two stages – an early stage that we have referred to in previous papers as the “familiarity check” (Reichle et al., 1998) or  $L_1$  (Pollatsek et al., 2005; Reichle, Rayner, & Pollatsek, 2003) and a later stage called the “completion of lexical access” or  $L_2$ . (The  $L_1$ – $L_2$  nomenclature was developed because we thought it was more agnostic with respect to the processes involved in the two stages of processing; in this paper, we will use both nomenclatures interchangeably.)

This distinction between  $L_1$  and  $L_2$  is the basis for the second core assumption of our model: that saccadic programming is decoupled from shifts of attention. This decoupling happens because the completion of the familiarity check on a given word causes the oculomotor system to begin programming a saccade to the next word, whereas the completion of lexical access on a given word causes attention to shift to the next word, so that lexical processing of that word can begin. The logic behind this assumption is that the familiarity check is a rapid assessment of whether or not the completion of lexical access is imminent. By “knowing” that lexical access of word  $n$  is imminent, the reader can begin programming a saccade to word  $n + 1$  and thereby minimize the fixation duration on word  $n$  without moving the eyes too soon (which would result in word  $n$  being viewed from a more distant location and might necessitate a regressive saccade to move the eyes back to word  $n$ ).<sup>3</sup> More generally,  $L_2$  can be viewed as a processing stage that needs to be reached before attention can be shifted to the next word, whereas  $L_1$  is a more preliminary stage that allows one to “cheat” and begin programming an eye movement reasonably safely with a high probability. Without such a cheat, the reader would be condemned to spend the first 100–150 ms of processing on each word (the time it takes to program and execute an eye movement) with the word in parafoveal vision.

The functional distinction between  $L_1$  and  $L_2$  can be conceptualized in at least three different ways (for an in-depth discussion of these alternative conceptualizations, see Rayner, Pollatsek et al., 2003). The first is based loosely on the idea that different types of lexical information about a word (e.g., its orthography, phonology, and meaning) become available to the reader at different points in time, and

<sup>3</sup> As will be discussed below, the results of several recent simulations that have used an adaptive “agent” that is capable of learning how to control its eyes to read efficiently suggest that this “strategy” of moving the eyes from word  $n$  to word  $n + 1$  prior to the full identification of word  $n$  is adaptive because doing so allows the reader to maximize his or her overall reading rate (Reichle & Laurent, 2005).

that a word's "familiarity" may be based on information that is available early during its identification. For example, one possibility is that the familiarity check is based on word-form information (e.g., orthographic and/or phonological), whereas the completion of lexical access is based on meaning. A second interpretation of the  $L_1$  vs.  $L_2$  distinction is consistent with the distinction in the memory literature between a rapidly available recognition process and a slower retrieval process (Atkinson & Juola, 1973, 1974; Yonelinas, 2002). By this conceptualization, the familiarity check is based on the rapid recognition of the word, whereas the completion of lexical access corresponds to the point in time at which specific information about a word (e.g., its meaning) has actually been retrieved from memory. (For an example of how such a model would account for a number of basic word-identification phenomena, e.g., the interaction between word frequency and spelling-to-sound regularity, see Reichle & Perfetti, 2003). Finally, a third interpretation of the  $L_1$  vs.  $L_2$  distinction is that the former corresponds to lexical access (i.e., the point at which a word's meaning is available), while the latter corresponds to post-lexical integration (i.e., the point at which the word's meaning has been interpreted in the context of whatever sentence it occurs).

Of course, these three possible interpretations of the  $L_1$  vs.  $L_2$  distinction that were just described are neither mutually exclusive (e.g., a familiarity check based on rapid recognition may weight word-form information more heavily than meaning) nor exhaustive, and at this time we prefer to remain agnostic on the issue. However, it is important to note that, because the duration of the first fixation on a given word is largely a function of the time that is required to complete the familiarity check on that word, it may be possible to rule out certain interpretations of the familiarity check by showing which variables do and do not influence first-fixation durations. (A few examples of the types of predictions that have been generated and tested are described below.)

In *E-Z Reader*, each time attention switches to a new word, there is some chance that it will be "identified" entirely through the top-down constraints that are imposed by higher-level language processing. This assumption that words are sometimes "guessed" from their context is consistent with reports that readers do sometimes skip and do not regress back to highly predictable words under conditions where a word is only visible if it is directly fixated (i.e., with a 1-word *moving-window*, where all words other than the one being fixated are replaced with random letters or strings of X's; Rayner, Well, Pollatsek, & Bertera, 1982). This result suggests that, whatever higher-level linguistic processing is being completed in parallel with the on-going lexical processing, it can – at least occasionally – intervene with lexical processing, making it unnecessary to identify some words. In our model, we simply assumed that the probability of this happening for a given word is equal to the word's predictability (as determined through cloze-task norms). When a word is "guessed" in this manner, the

completion of  $L_1$  is not necessary, so that the duration of this process is effectively set equal to 0 ms. (The meanings of "guessed" words still need to be processed, however, so that time that is necessary to complete  $L_2$  is always equal to some non-zero value; see below.)

With the preceding assumptions, only a small proportion of words will be "guessed" (e.g., many of these instances involve the function word "the"); the majority of words will instead be identified, with the time that is needed to do so being a function of the word's predictability and its frequency of occurrence (as tabulated in the norms of Francis & Kučera, 1982).<sup>4</sup> The relationship between these two variables and the time that is needed to complete  $L_1$ ,  $t(L_1)$ , is specified by Eq. (1), where  $\alpha_1$  (= 122 ms) is an intercept parameter that represents the maximal amount of time that is needed to process a word, and  $\alpha_2$  (= 4 ms) and  $\alpha_3$  (= 10 ms) are free parameters<sup>5</sup> that scale the degree to which the natural logarithm of the word's frequency and predictability decrement the maximal processing time. (The appendix contains a table showing all of the model's parameters, a short description of their interpretation, and their best-fitting values.) The manner in which a word's frequency and predictability are combined to determine  $t(L_1)$  differs from earlier versions of our model (Reichle et al., 1998, 1999, 2003); it was adopted to account for the additive effects of word frequency and predictability on fixation durations (Rayner, Ashby, Pollatsek, & Reichle, 2004).

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

Eq. (1) gives the mean time to complete the familiarity check on a word of a given frequency and predictability; the actual time that is needed to complete the familiarity check on a given word during a Monte-Carlo trial of a simulation is a random deviate that is sampled from a gamma distribution with the mean given by Eq. (1) and a standard deviation equal to .22 of the mean.

<sup>4</sup> This is not meant to imply that there are not other important variables that affect how long it takes to identify words (e.g., the age at which a word is first learned; Juhasz & Rayner, 2003, 2005). Our decision to focus exclusively on word frequency and predictability reflects that fact that information about these variables is relatively easy to obtain, and the fact that both variables have been shown to affect word identification in both natural reading and a variety of other tasks (e.g., pronunciation and lexical decision; Schilling, Rayner, & Chumbley, 1998).

<sup>5</sup> The model's best-fitting parameter values were found by completing grid-searches of the parameter space as described in the appendix of Reichle et al. (1998). Our goodness-of-fit measure was the *root-mean-squared deviation (RMSD)* between the mean observed and predict first-fixation durations, gaze durations, probability of making a single fixation, and probability of making two or more fixations for five frequency classes of words. Smaller values of our index thus indicate a better fit of the model to the data. Previous versions of our model have given the following best fits: *E-Z Reader 5* (Reichle et al., 1998), RMSD = .198; *E-Z Reader 6* (Reichle et al., 1999), RMSD = .218; *E-Z Reader 7* (Reichle et al., 2003), RMSD = .088; and *E-Z Reader 8* (Rayner, Liversedge, & White, 2005), RMSD = .109. The current model, *E-Z Reader 9*, gave an overall fit that was comparable to our best published fits: RMSD = .153.



One other assumption regarding the familiarity check is that the rate at which this stage of lexical processing is completed is modulated by visual acuity. This assumption is based on the well-known fact that the type of high visual acuity that is needed to extract the features of letters is largely limited to the *fovea*, or central 2° of the visual field, and that visual acuity decreases rapidly going from the center of the fovea to the *parafovea* (which extends 5° out to either side of the center of vision) to peripheral vision. This drop off in visual acuity explains why word identification becomes slower and more prone to error as the angular disparity between the center of the fovea and the center of the word being processed increases (Lee, Legge, & Ortiz, 2003; Rayner & Morrison, 1981).

To account for these facts, we adopted the assumption that the time that is needed to complete the familiarity check (i.e., the random deviate that is sampled from a gamma distribution having a mean defined by Eq. (1)) is modulated by visual acuity. This is specified by Eq. (2), where  $t_{\text{acuity}}(x)$  is a function that increases the duration of  $t(L_1)$  as visual acuity decreases. In Eq. (2),  $\varepsilon$  ( $= 1.15$ ) is a free parameter that modulates the effect of visual acuity, which in our model is defined in terms of the mean absolute *distance* (i.e., number of character spaces) between the current fixation location and each of the letters in the word being processed ( $N$  is the number of letters in the word). The value of  $\varepsilon$  was selected so that the familiarity check would be slowed by factors of 1.15, 1.32, and 1.52 when the first letter of 3-, 5-, and 7-letters words (respectively) is fixated (relative to when a 1-letter word is directly fixated). It thus takes more time to identify long words and words that are farther from the fovea (i.e., the current fixation location). Both of these predicted outcomes are consistent with empirical results; as already mentioned, word identification is slower and less accurate in peripheral vision (Lee et al., 2003; Rayner & Morrison, 1981) and longer words do take longer to identify than shorter words (Just & Carpenter, 1980; Rayner & McConkie, 1976; Rayner, Sereno, & Raney, 1996).

$$t_{\text{acuity}}(t(L_1)) = t(L_1)e^{\Sigma|\text{distance}|/N}. \quad (2)$$

Our final assumption regarding word identification concerns the second stage of lexical processing,  $L_2$ . As already mentioned,  $L_2$  can be conceptualized in several different ways. As the *E-Z Reader* model is currently instantiated, the extra time that is needed to complete  $L_2$  is some fixed proportion of  $t(L_1)$ . This relationship is specified by Eq. (3), where  $t(L_2)$  is the time that is needed to complete  $L_2$ ,  $t(L_1)$  is the time that is specified by Eq. (1) prior to sampling from the gamma distribution, and  $\Delta$  ( $= .5$ ) is the free parameter that determines what proportion of  $t(L_1)$  is required to complete  $L_2$ . Finally, the actual time that is required to complete  $L_2$  for a given word during a given Monte-Carlo simulation trial is also a random deviate that is sampled from a gamma distribution with a mean equal to  $t(L_2)$  and a standard deviation equal to .22 of the mean.

$$t(L_2) = \Delta(L_1). \quad (3)$$

A few points regarding the completion of lexical access warrant discussion. The first is that the completion of lexical access, in contrast to the familiarity check, is obligatory. In other words, unlike  $t(L_1)$ , which does not have to be completed (i.e., its value can be set equal to 0 ms) if a word is predicted from its sentence context,  $t(L_2)$  is always equal to some fixed proportion of the time that would have been required to complete  $L_1$  if the word had not been predicted (i.e., the non-zero value that is given by Eq. (1)). This assumption that  $t(L_2)$  always requires some minimal amount of time to complete reflects our conceptualization of  $L_2$  as having something to do with the processing of a word's meaning (either its access or its integration), and that, irrespective of how a word's meaning is obtained (i.e., entirely through top-down constraints in the case of highly predictable words vs. the more bottom-up route specified by Eqs. (1) and (2)), the process of accessing and/or integrating a word's meaning is necessary if the reader is to understand whatever is being read.

The second point regarding the completion of lexical access that warrants discussion is that  $t(L_2)$  is not modulated by visual acuity. This assumption also follows from our conceptualization of  $L_2$  as being a later stage of lexical processing – one that is impervious to degradation in the quality of the visual information that comes from viewing a word in peripheral vision. This assumption is also consistent with the results of a recent experiment (Reingold & Rayner, 2005) showing that the visual degradation of a word (e.g., by making its letters faint) lengthens the fixation duration on that word (i.e., the degradation increase the duration of  $L_1$ ) but does not affect the fixation duration on the subsequent word (i.e., it does not increase the duration of  $L_2$ ). (This experiment is described in more detail, below.)

One final point about the completion of lexical access concerns the model's predictions regarding word-identification latencies: If one includes the 50 ms that is necessary for visual processing time, then the *E-Z Reader* parameters specify the mean minimum (in cases where predictability  $< 1$ ) and maximum times to identify words as being equal to 151 and 233 ms, respectively. (These estimates ignore the effects of visual acuity, which would in most instances increase the estimated values.)

This description of how visual processing, attention, and lexical processing interact in guiding the eye movements of skilled readers describes the “front end” of the model. Of course, a model of eye-movement control, by definition, has to say something about oculomotor control. Fig. 1 shows the oculomotor system, and how this system is related to the parts of the model that have already been described.

Our first assumption regarding saccadic programming is based on results suggesting that saccades are programmed in two stages: a *labile stage* ( $M_1$ ) that is subject to cancellation by the initiation of subsequent saccadic programs, and

a *non-labile stage* ( $M_2$ ) that is not subject to cancellation (Becker & Jürgens, 1979; Leff, Scott, Rothwell, & Wise, 2001; McPeck, Skavenski, & Nakayama, 2000; Molker & Fisher, 1999; Vergilino & Beauvillain, 2000). In our simulations, the actual times that are required to complete the two stages of programming are random deviates that are sampled from a gamma distributions having means equal to 100 and 25 ms (for  $M_1$  and  $M_2$ , respectively) and standard deviations equal to .22 of the means. With these parameter values, the mean *saccadic latency*, or minimal amount of time that is needed to detect a saccade target and then move the eyes to its location, is predicted to be approximately 175 ms (i.e., the sum of the eye-to-mind lag and the mean durations of the two stages of saccadic programming). This estimate corresponds closely to empirical estimates of the saccadic latency (Becker & Jürgens, 1979; McPeck et al., 2000; Rayner, Slowiaczek, Clifton, & Bertera, 1983).

We also assume that the labile stage of programming consists of two sub-stages which, for the sake of simplicity, each take exactly half of the time ( $\xi = .5$ ) that is required for  $t(M_1)$  to complete. The first of these sub-stages is devoted to general system preparation, during which the oculomotor system is engaged and made ready to begin programming a saccade. During the second sub-stage, the coordinates of the spatial target (which in our model is always the optimal-viewing position of the targeted word) are translated into the appropriate saccade distance or muscle force that is necessary to move the eyes to their target.

Two important consequences emerge from the disparity between the time when a word is identified and the time when a saccade leaving it is executed. These consequences can best be explained using Fig. 2. The  $x$ -axis of this figures shows one measure of word-processing difficulty (e.g., as indexed by a word's frequency of occurrence in printed text), and the  $y$ -axis shows the means cumulative times that are required to complete the two stages of word identification,  $t(L_1)$  and  $t(L_2)$ , and the time needed to program a saccade, which is equal to  $t(M_1) + t(M_2)$ . An important point to remember from the earlier description of the model is that attention will often shift from word  $n$  to word  $n + 1$

before the program to move the eyes from word  $n$  to word  $n + 1$  has been completed. When this happens, lexical processing of word  $n + 1$  begins immediately, allowing the word to be processed from the parafovea. The amount of time that is spent engaged in this type of parafoveal processing is represented by the shaded area in Fig. 2. Notice that the amount of parafoveal processing that can be completed on word  $n + 1$  when a given word  $n$  is fixated varies as a function of how difficult that word  $n$  is to process; difficult words afford less parafoveal processing of subsequent words than easy words. As the figure shows, this stems from the fact that the disparity between  $t(L_1)$  and  $t(L_2)$  increases as the difficulty of word processing increases, in conjunction with the fact that the saccadic latency remains constant. The consequences of this are twofold. First, any difficulty that is associated with processing word  $n$  will result in less parafoveal processing of word  $n + 1$ , which will in turn cause processing difficulty to “spill over” onto word  $n + 1$ , inflating the durations of any subsequent fixations on that word. Second, any cost that is incurred on word  $n + 1$  that may come from preventing normal parafoveal preview of that word (e.g., as can be done using gaze-contingent procedures, like the *boundary paradigm*, where a target word is replaced by random letters or X's until it is actually fixated; Rayner, 1975) will be more pronounced if word  $n$  is easy to process because such cases allow for more parafoveal processing. These consequences are consistent with the literature; spillover effects have been well documented (Rayner & Duffy, 1986; Rayner et al., 1996), as have interactions between the difficulty of foveal processing and preview benefit (Henderson & Ferreira, 1990; Inhoff, Pollatsek, Posner, & Rayner, 1989; Kennison & Clifton, 1995; Rayner, 1986; White, Rayner, & Liversedge, 2005).

Our assumptions about where saccades are targeted and where they actually go to are largely derived from the work of O'Regan, McConkie, and their colleagues, as well as our own work (McConkie, Kerr, Reddix, & Zola, 1988, 1991; O'Regan, 1990, 1992; O'Regan & Lévy-Schoen, 1987; Rayner, 1979; Rayner et al., 1996; Reichle et al., 1999). This work suggests that the eyes are targeted to land on the optimal-viewing positions of words, but because of motor error often fail to land on their intended targets. As a result, the distributions of fixation landing sites tend to resemble truncated Gaussians that are centered near the middle of a targeted word, with the missing tails reflecting those saccades where the eyes undershot or overshot their intended targets. The landing-site distributions also tend to shift towards the beginning of the target words and to become more variable as the saccade length increases, and as the fixation duration on the *launch-site* word (i.e., the word from where the saccade originated) decreases.

To capture these general patterns within our model, we started with the assumption that the length of the saccade (in character spaces) that is actually executed is the sum of three components – the actual intended saccade length, a *systematic error* component, and a *random error* component.

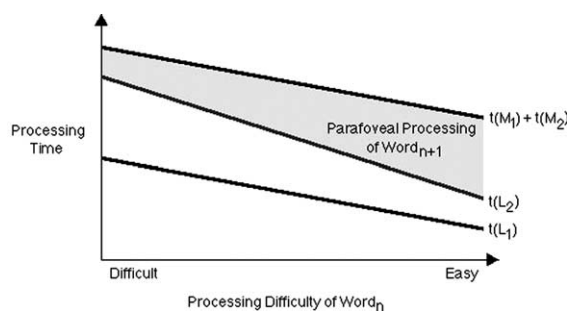


Fig. 2. Relative time course of lexical processing and saccadic programming, and how the disparity between the two stages of lexical processing results in parafoveal preview that is modulated by the lexical processing difficulty of the fixated word.

The systematic error component is an amount by which the saccade will tend to undershoot or overshoot its intended target, and is a function of both how much the intended saccade length deviates from a preferred saccade length, and of the fixation duration on the launch-site word. The systematic error tends to decrease as both the deviation between the intended and preferred saccade lengths decrease, and as the fixation duration on the launch-site word increases. These relationships are specified by Eq. (4), where  $\Psi$  is a parameter that represents the preferred saccade length (which in English is equal to 7 character spaces), and  $\Omega_1 (= 7.3)$  and  $\Omega_2 (= 3)$  are free parameters that modulate the degree to which the launch-site fixation duration affects the systematic error.

$$\begin{aligned} \text{Systematic error} &= (\Psi - \text{intended length}) \\ &\times [\Omega_1 \ln(\text{fixation duration})/\Omega_2]. \end{aligned} \quad (4)$$

The second source of saccadic error, the random error component, is meant to reflect true (random) motor error. As such, this error is a random deviate that is sampled from a Gaussian distribution having a mean equal to zero and a standard deviation that is a function of the intended saccade length, as given by Eq. (5). In this equation,  $\eta_1 (= .5)$  and  $\eta_2 (= .15)$  are free parameters that determine how much the variability of the random error increases with the intended saccade length.

$$\text{Random error} = \eta_1 + \eta_2 \text{ intended length}. \quad (5)$$

Our third and final assumption regarding saccades concerns refixations and is similar to what is assumed in the most recent version of the SWIFT model of eye-movement control (Engbert, Nuthmann, Richter, & Kliegl, 2005) – that upon fixating a word, the reader can program and execute a corrective refixation saccade to move the eyes to a better viewing location. Because initial fixations landing near the beginnings/endings of words do not allow efficient lexical processing due to the poorer visual acuity of many letters in the word from such locations (see Eq. (2)), a rapid corrective saccade will (on average) move the eyes closer to the center of the word so that lexical processing can proceed more rapidly from this better viewing location. As specified by Eq. (6), the probability of initiating a refixation saccade,  $p$ , is a function of the absolute distance (in character spaces) between the initial landing position on a word and the word’s optimal viewing position, as scaled by the free parameter  $\lambda (= .09)$ . Because the potential size of the absolute distance increases with word length, longer words are more likely to be the recipients of refixations than shorter words (Vergilino & Beauvillain, 2000).

$$p = \lambda |\text{optimal viewing position} - \text{initial landing position}|. \quad (6)$$

Finally, for it to be plausible that such “intelligent” refixation saccades could be programmed, it was necessary to assume that the “decision” about whether or not to initiate a corrective eye movement could be made only after a

delay that is greater than the amount of time that is necessary to get the information about where the initial fixation is located from the eye to the brain. This delay was sampled from a gamma distribution with a mean equal to the free parameter  $R (= 117 \text{ ms})$ ; because feedback about the initial fixation location is based on visual information, the value that was sampled was restricted so that  $t(R) > V$  (i.e., the duration of the eye-brain lag). Thus, upon fixating a word, a refixation saccade (obeying Eqs. (4) and (5), just like inter-word saccades) is initiated if: (a) another labile saccade has not already been initiated and (b) a saccade has not already been initiated to move the eyes to the next word. These two restrictions are sufficient to prevent refixation saccades from canceling saccades that would otherwise cause the eyes to move forward in the text.

This concludes our description of the *E-Z Reader* model. In the next section of this paper, we will present the simulation results of several “benchmark” phenomena that – we believe – any viable model of eye-movement control should be able to explain.

### 3. Simulations of “benchmark” phenomena

Each of the Monte-Carlo simulations that are reported in this section are based on 1000 statistical subjects and use the same set of free parameter values that were reported in the previous section of the article (see Appendix). The first of these simulations was done to evaluate the model’s overall capacity to fit a corpus of 48 sentences that were used in an eye-tracking experiment by Schilling et al. (1998). The sentences were 8–12 words in length. Before completing the simulation, the words were divided into five frequency classes (1–10, 11–100, 101–1000, 1001–10,000, and 10,001 + per million), and six word-based means were computed for the words in each class: the first-fixation, single-fixation, and gaze durations, and the probabilities of skipping, making one fixation, and making two or more fixations. We excluded those trials in the corpus that contained inter-word regressions because such instances can reflect difficulty with higher-level language processing and are thus outside of the scope of our model. (Approximately 36% of the data were retained for our analyses.) We also excluded the first and last words of each sentence because the first and last fixations are often anomalous due to factors that are unrelated to normal reading (e.g., the sudden appearance of the sentence at the beginning of the trial). This corpus was used in all of our previous simulations (see Footnote 1) and in the simulations that are reported below using our current model: *E-Z Reader 9*.

#### 3.1. Word-frequency effects

Fig. 3 shows the results of the first simulation. The top panel shows the mean observed and simulated fixation-duration measures for the five frequency classes of words, and the bottom panel shows the mean observed and simulated fixation-probability measures. The model accounts

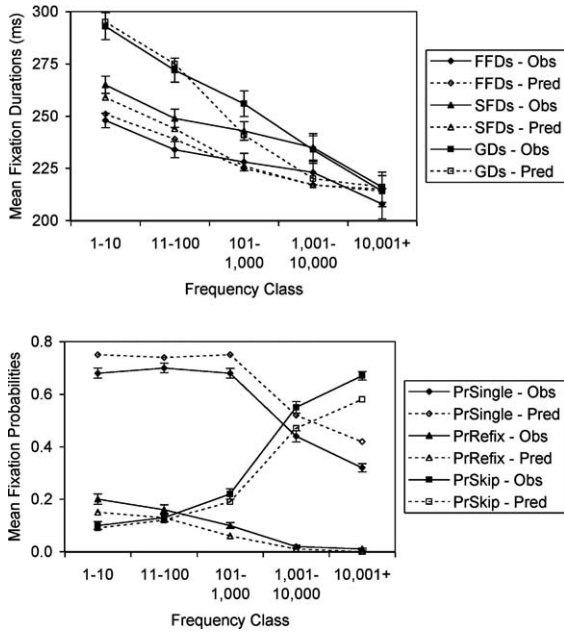


Fig. 3. Top panel: Mean observed and predicted first-fixation, single-fixation, and gaze durations for the five frequency classes of words in the Schilling et al. (1998) sentence corpus. Bottom panel: Mean observed and predicted probabilities of skipping, making one fixation, and making two or more fixations for the Schilling et al. corpus.

for 89% of the variance among the mean fixation-duration measures, and 96% of the variance among the mean fixation-probability measures. We also examined the model's capacity to account for the distributions of fixation durations. Fig. 4 shows the distributions of observed and simulated first-fixation and gaze durations for each of the frequency classes. A visual comparison of the observed and simulated distributions indicates that the model also does a fairly good job accounting for the variability of the fixation-duration measures.

One objective of the Schilling et al. (1998) experiment was to examine word frequency effects on a set of length-controlled target words. In their experiment, half of the target words were high frequency (mean = 141 per million) and half were low frequency (mean = 2 per million). We examined the model's performance on these same target words. Sizeable word-frequency effects were observed on both the first-fixation durations (mean = 31 ms) and gaze durations (mean = 50 ms). Our model predicted a 22-ms frequency effect on the first-fixation durations and a 40-ms effect on the gaze durations.

This first simulation shows that our model can account for both aggregate (sentence corpus) data and data from specific target words. The model is successful largely because the duration of the first fixation on a given word is determined by how long it takes to complete the familiarity check on that word (remember that the familiarity check causes the oculomotor system to initiate a saccadic program), and because the amount of time that is required to complete the familiarity check on a word is a function

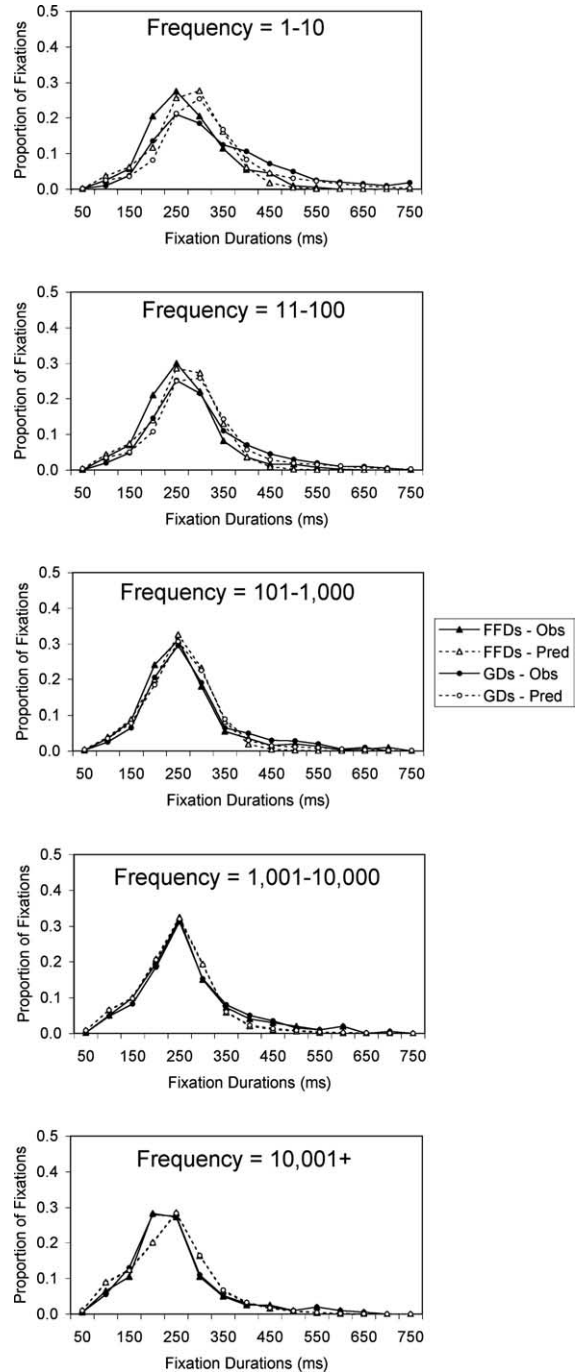


Fig. 4. Observed and predicted distributions of first-fixation and gaze durations for the five frequency classes of words in the Schilling et al. (1998) sentence corpus.

of its frequency (see Eq. (1)). Another factor that contributes to the predicted word frequency effects is the fact that word frequency is negatively correlated with word length, and in our model this correlation will mean that familiarity check will on average require more time to be completed on long words than on short words (see Eq. (2)).

The next pair of simulations was completed to show how the model accounts for other frequency-related



phenomena. The first of these simulations shows how our model account for the spillover effects that occur when the processing difficulty of word  $n$  “spills over” onto word  $n + 1$ , inflating the gaze durations on that word, too. To demonstrate this, we manipulated the frequency of the Schilling et al. (1998) target words (which will be designated as word  $n$  for the sake of exposition). In one condition of the simulation, the frequency of word  $n$  was set equal to 141 per million; in the other condition, the frequency of word  $n$  was set equal to 2 per million. (The lengths and cloze predictabilities of both words were set equal to 6 letters and zero, respectively.) This manipulation resulted in a 19-ms frequency effect on the word  $n$  gaze durations, and a 9-ms spillover effect on the word  $n + 1$  gaze durations. This result is consistent with reports that spillover effects are typically about one quarter of the size of frequency effects on the preceding words (Rayner & Duffy, 1986; Rayner & Pollatsek, 1989).

Of course, the fact that the model predicts spillover effects is not unexpected. As already mentioned, the disparity in the times that are needed to complete  $L_1$  vs.  $L_2$  (see Eq. (3) and Fig. 2) will cause any parafoveal processing of word  $n + 1$  that is completed from word  $n$  to vary as a function of the processing difficulty of word  $n$ . This property of the model leads to the prediction that was tested in our next simulation: that the processing difficulty of word  $n$  should interact with any cost that comes from denying normal parafoveal processing of word  $n + 1$ . To test this prediction, we ran a simulation of a  $2 \times 2$  experiment in which we orthogonally manipulated the frequency of word  $n$  and whether or not parafoveal processing of word  $n + 1$  occurred. The frequency of word  $n$  was manipulated to be high frequency (500 per million) in one condition and low frequency (1 per million) in the other. (To ensure that any predicted effects were due to word frequency, the length and cloze predictability of word  $n$  was set equal to 6 letters and 0, respectively. Similarly, the frequency, length, and predictability of word  $n + 1$  was set equal to 1 per million, 6 letters, and 0, respectively.) In the two conditions without parafoveal processing, the processing of word  $n + 1$  started with 50 ms of visual processing, and was only allowed to start after either word  $n + 1$  or the blank space immediately to the left of the word had been fixated. Under these conditions, the model predicted a 7-ms decrement in the size of the preview benefit (as measured using the duration of the first fixation on word  $n + 1$ ) when word  $n$  was low frequency. In other words, the size of the fixation-duration decrement on word  $n + 1$  that results from normal parafoveal processing is 7 ms smaller when word  $n$  is a low-frequency, difficult-to-process word. This predicted reduction in preview benefit, although seemingly small in magnitude, it is nevertheless consistent with empirical observations (Henderson & Ferreira, 1990; Inhoff et al., 1989; Kennison & Clifton, 1995; White et al., 2005). We therefore contend that our model provides an account of both word frequency and its secondary effects of the processing of subsequent words.

### 3.2. Other lexical variables

The next two simulations show that the model can account for the effects of a word’s predictability and its length. In the first simulation, we varied the predictability of the Schilling et al. (1998) target words while controlling both their frequency (= 100 per million) and length (= 6 letters). In the second simulation, we varied the length of the target words while controlling their frequency (= 100 per million) and predictability (= 0). The predicted effects of word predictability and length are shown in Fig. 5. Note that these two variables affect both measures of fixation duration and fixation probability. This is not surprising. One assumption in our model is that word predictability directly affects the time that is required to complete the familiarity check (see Eq. (1)). In a similar manner, word length affects the time required to complete the familiarity check, although it does so indirectly, through the slow down in processing of longer words that stems from limitations of visual acuity (see Eq. (2)). The model thus predicts that the effects of both predictability and word length reflect the rate of lexical processing. The first of these conjectures is interesting because it implies that whatever variables are subsumed under predictability (e.g., syntactic processing) can influence the earliest stage of word identification.

### 3.3. Skipping costs

*E-Z Reader* predicts longer fixation durations on word  $n$  when word  $n - 1$  is skipped as compared to when it is not. The prediction stems from the fact that, when word  $n - 1$  is skipped, whatever parafoveal processing of word  $n$  that is completed is done from a more distant viewing location (word  $n - 2$ ) than if word  $n - 1$  is fixated. Our current model predicts a 29-ms skipping cost on the Schilling et al. (1998) target words; this prediction is at least qualitatively consistent with the 50-ms cost that was actually observed in the Schilling et al. corpus (see Reichle et al., 1998).

Our model also predicts longer fixation durations on word  $n$  when word  $n + 1$  is skipped as compared to when it is not. The prediction stems from the fact that, in order to skip word  $n + 1$ , the program to move the eyes to word  $n + 1$  must be canceled and replaced by a program to move the eyes to word  $n + 2$ . The time that is lost canceling and then re-programming the saccade causes the fixation duration on word  $n$  to be longer than it otherwise would have been. Although this predicted cost is a bit controversial, with some reports of failures to find such costs (Radach & Heller, 2000), other reports have confirmed their existence (Kliegl & Engbert, 2005; Pollatsek, Rayner, & Balota, 1986; Pynte, Kennedy, & Ducrot, 2004; Rayner et al., 2004). Our current model predicted a 18-ms cost on the Schilling et al. (1998) target words; this result again qualitatively consistent with the 38-ms cost that was actually observed in the corpus.

### 3.4. Landing-site distributions

As already mentioned in our discussion of our model’s assumption regarding the execution of saccade, it has been observed (McConkie et al., 1988, McConkie, Zola, Kerr, Bryant, & Wolff, 1991; Rayner, 1977; Rayner et al., 1996) that the distributions of landing sites on words resembled truncated Gaussians, with the missing tails being due to saccades that either overshoot or undershot their intended targets. These landing-site distributions tended to be centered near the middle of words, but also showed a tendency to shift towards to beginning of the words and to become more variable as the saccade distance increased and as the fixation duration on the launch site word decreased. Our model’s assumption regarding saccade execution were motivated by these findings, and by trying to test Reilly and O’Regan’s (1998) claim that serial-attention models like *E-Z Reader* would not be able to account for these findings.

Fig. 6 shows the landing-site distributions that were generated by our model on 4-, 5-, 6-, and 7-letter words as a

function of the saccade length (i.e., the location of the saccade launch site). The figure clearly shows that the distributions resemble truncated Gaussians that both shift towards the beginning of the words and become more variable as the saccade length increases. Fig. 7 shows the mean locations of the landing-site distributions on 6-letter words as a function of both the saccade length and whether the launch-site fixation duration was short (<150 ms) or long (>350 ms). As Fig. 7 shows, the increase in the landing-site variability that results from increasing saccade length diminishes as the fixation duration on the launch site increases. This is evident in the figure if one compares the landing-site distribution means following short launch-site fixation durations to those following long launch-site fixation durations; there is much less spread among the means following the longer launch-site fixations. Together, the results of this simulation indicate that – contrary to Reilly and O’Regan’s (1998) – our model can account for the motor error that is associated with moving the eyes while at the same time accounting for all of the other variables that have already been reported.

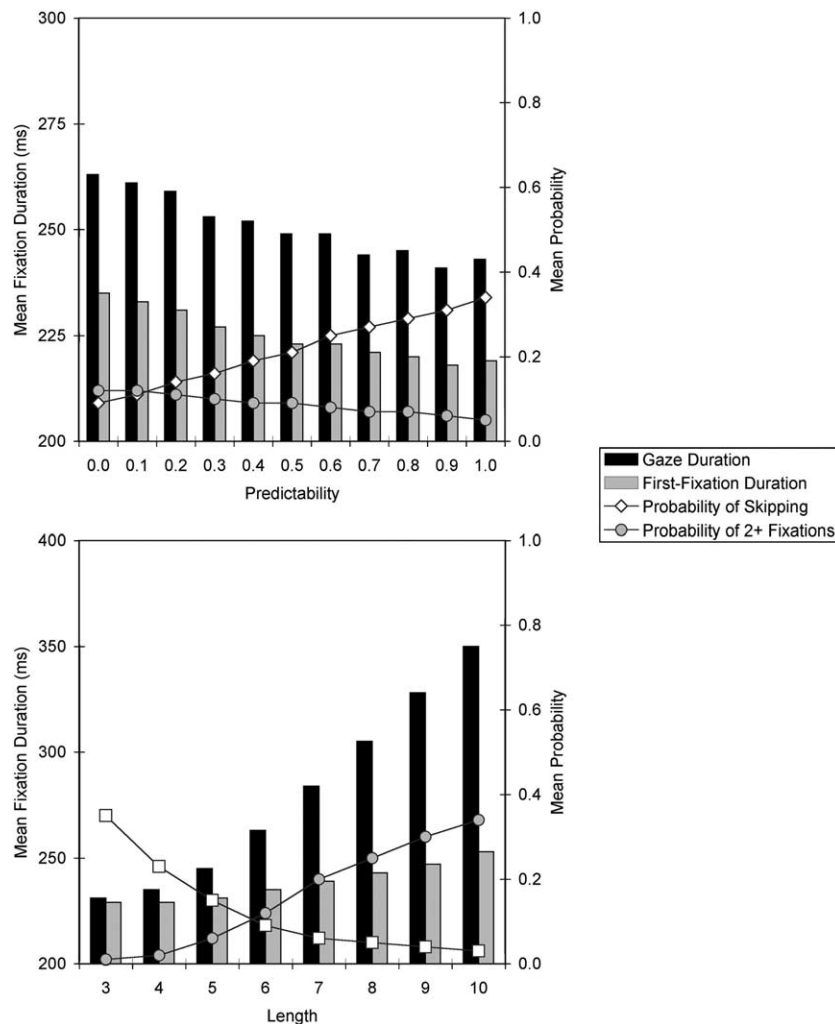


Fig. 5. Top panel: Predicted effects of word predictability on first-fixation and gaze durations, and on the probability of skipping and making refixations. Bottom panel: Predicted effects of word length on first-fixation and gaze durations, and on the probability of skipping and making refixations.

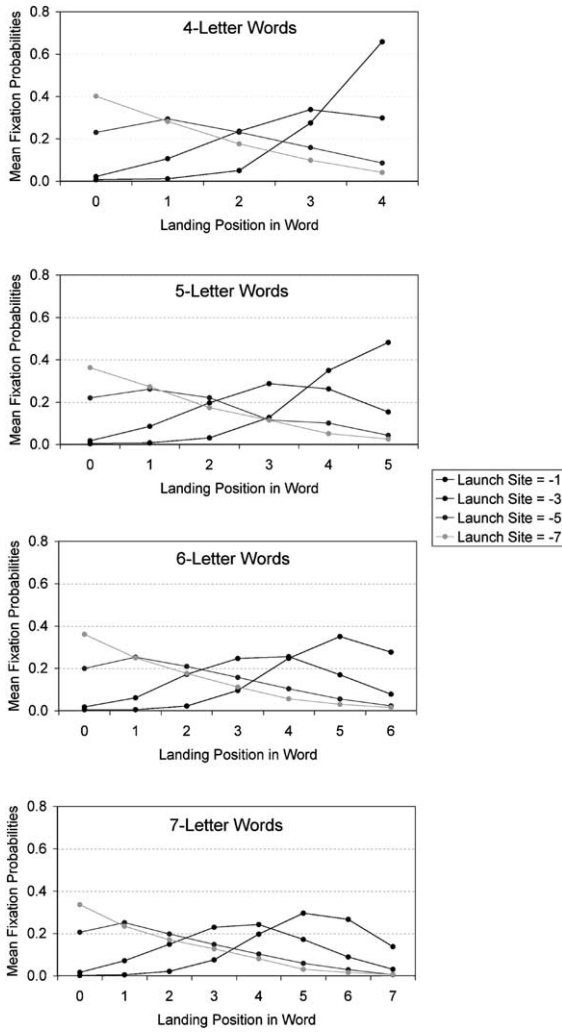


Fig. 6. Predicted landing-site distributions on 4-, 5-, 6-, and 7-letter words, as a function of saccade length (i.e., the location of the saccade launch site).

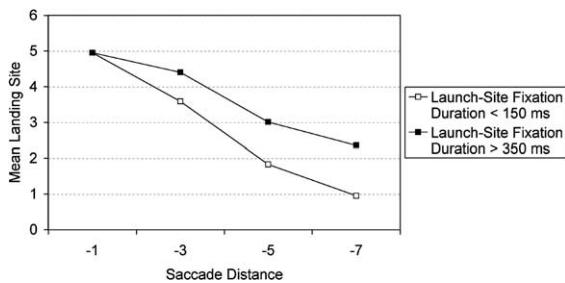


Fig. 7. Predicted means of landing-site distributions on 6-letter words, as a function of saccade length (i.e., the location of the saccade launch site) and whether the launch-site fixation duration was short (<150 ms) or long (>350 ms).

3.5. Interim conclusions

This exhausts the list of the phenomena that we take to be “benchmarks” for any viable model of eye movements during reading. In the next section, we will briefly describe

the results of a few new simulations of experiments that have used gaze-contingent paradigms (e.g., the *disappearing-text paradigm*; Rayner et al., 2005). We believe that the results from these experiments are especially diagnostic because of the severe constraints that the gaze-contingent paradigms place on the possible time course of visual, oculomotor, and cognitive processing. We therefore believe that these paradigms will prove to be especially problematic for the other models of eye-movement control to explain.

4. New simulations of gaze-contingent paradigms

The pair of simulations that are reported in this section have been described in more detail elsewhere (see Pollatsek et al., 2005) but are discussed here for the sake of documenting the model’s theoretical scope and to elucidate how it explains phenomena that we believe are problematic for other models of eye-movement control. For practical reasons, these simulations were not completed using the actual experimental materials because doing so would have necessitated knowing the frequencies and predictabilities of all of the words in the corpora, and would have required a considerable amount of preparation to exclude trials containing regressions and to calculate the various word-based measures that are necessary to fit the model to the data (see Footnote 5). As a result, we opted to instead use the Schilling et al. (1998) sentences and the parameter values that were used in our earlier simulations as a “baseline” condition against which the predicted consequences of the manipulations of interest (e.g., disappearing text) could be evaluated. Thus, one could argue that the three simulations that are reported below are conservative estimates of how the model would fare in accounting for the observed experimental results; the simulation results would be expected to improve if they were repeated using the actual experimental materials and if the different values of the model’s free parameters were allowed to vary.

4.1. The boundary paradigm

In our first simulation, we examined whether or not the model could explain the results from experiments that have used the boundary paradigm (Rayner, 1975). In the version of this paradigm that we simulated, the letters of pre-specified target words are replaced by X’s or random letters until either the word or the blank space immediately to the left of the word was fixated. The boundary paradigm is therefore similar to the *moving-window paradigm* (in which all of the letters outside of a pre-specified viewing “window” are replaced with X’s; McConkie & Rayner, 1975) in that both procedures can be used to assess the cost that comes from the absence of normal parafoveal processing. However, there are two important differences that make the results of the boundary-paradigm experiments more informative: first, it provides a method for precisely evaluating the consequences of allowing vs. not allowing

parafoveal processing on specific target words; second, it is less apt to promote idiosyncratic reading strategies because participants in boundary-paradigm experiments are usually unaware of the display changes.

Hyönä, Bertram, and Pollatsek (2004) recently completed a meta-analysis of the results from seven boundary-paradigm experiments and found *preview benefits* (i.e., differences in the gaze durations on target words due to allowing vs. not allowing parafoveal processing) to be 40–50 ms. Using the Schilling et al. (1998) target words, our model predicted a 39-ms preview benefit on first-fixation durations and a 46-ms preview benefit on the gaze durations. Again, the close correspondence between the observed and predicted values in this simulation lends support to our claim that our model provides very accurate estimates of several key parameter values and – more importantly – an accurate account for the amount of parafoveal processing that is observed in reading. This last claim can be more fully appreciated if one considers that, in our simulation of the no-preview condition, the visual processing stage must “re-start” as soon as the eyes first land on the target words. In our model, this process takes 50 ms to complete (i.e., the duration of the eye-to-mind lag). One might therefore be inclined to ask: Why is the cost in the no-preview condition not much greater than the duration of the eye-to-mind lag given that processing in the preview condition starts in the middle of the prior fixation, and continues during the saccade and until the new, foveal information displaces it? The answer is that, even though the visual processing only begins when the word is fixated in the no-preview condition (which results in a 50-ms delay in lexical processing), the advanced processing in the preview condition is not that efficient. That is, the 50+ ms head start on lexical processing in the preview condition is from a distant viewing location, where visual acuity is poor. This makes the effective savings from processing the preview information considerably less than the amount of time spent on it, and it is even a bit less than the total duration of the eye-to-mind lag. The fact that our model captures these fairly subtle constraints lends further support to our assertion regarding the model’s descriptive adequacy.

#### 4.2. The disappearing-text paradigm

In our second simulation, we were interested in finding out if our model could account for the results of a paradigm in which either the fixated word or both the fixated word and the word immediately to its right disappear after some fixed amount of time after the beginning of the first fixation on a word (Liversedge, Rayner, White, Vergilino-Perez, Findlay, & Kentridge, 2004; Rayner, Liversedge, White, & Vergilino-Perez, 2003; Rayner et al., 2005). For example, Rayner et al. (2005) manipulated both the frequency of the target word (word  $n$ ) and whether word  $n$  or word  $n$  and  $n + 1$  disappeared 60 ms after word  $n$  was fixated. Relative to control conditions in which neither

word disappeared, the conditions in which word  $n$  disappeared resulted in fairly normal reading. In contrast, the conditions in which word  $n$  and word  $n + 1$  disappeared resulted in approximately a 30% decrement in the overall reading rate. These results are somewhat paradoxical because a number of experiments have shown that the overall reading rate remains more-or-less normal when, with each new fixation, the word that is fixated is replaced by a mask after 50–60 ms (Ishida & Ikeda, 1989; Liversedge et al., 2004; Rayner, Liversedge et al., 2003; Rayner, Inhoff, Morrison, Slowiaczek, & Bertera, 1981). We believe that the disruption that is caused when the word to the right of fixation also disappears may be especially informative for evaluating one of the key issues regarding eye-movement control during reading: whether attention is allocated to one word at a time, or whether it is instead allocated in parallel to more than one word. Our intuition was that serial-attention models, like *E-Z Reader*, could provide a natural explanation for the results, but that parallel-attention models could not.

To examine if our model could handle the Rayner et al. (2005) results, we ran six simulations in which three types of display changes (no display change vs. word  $n$  disappears vs. words  $n$  and  $n + 1$  disappear) were orthogonally varied with the frequency of word  $n$  (1 vs. 105 per million, as given in the CELEX database; Baayen, Piepenbrock, & Gulikers, 1995). In the four disappearing text conditions, the word(s) disappeared 60 ms after either the blank space immediately to the left of word  $n$  or any of the character spaces to the right of this space were initially fixated. To complete this simulation, it was necessary to introduce a 500-ms fixation “deadline” to ensure that the eyes would continue to move forward in cases where lexical processing had stopped (this happened whenever the model shifted attention to a word that had already disappeared).<sup>6</sup> Because the value of this deadline is arbitrary, we will report two dependent measures: the gaze durations on words  $n$  and  $n + 1$ , and the proportion of our Monte-Carlo simulation trials in which the model shifted its attention to a word that had already disappeared. (This last measure is an index of how disruptive the different conditions are, and in contrast to the gaze durations, this measure does not depend upon the value of the saccade deadline.)

Fig. 8 shows the predicted gaze durations on word  $n$  (top panel) and word  $n + 1$  (bottom panel) as a function of the frequency of word  $n$  and the three display-change conditions. Several trends are clear. The first is that the

<sup>6</sup> This situation is problematic for the model because, whenever lexical processing stops, a saccade to move the eyes to a new location cannot be initiated. (Remember that the saccadic programs are initiated by the familiarity check.) To avoid this “catch-22” situation, we incorporated the 500-ms deadline so that a saccadic program directed towards the attended word would be initiated. This additional assumption is thus not meant to be part of our model, but is instead adopted only to make the simulation possible.



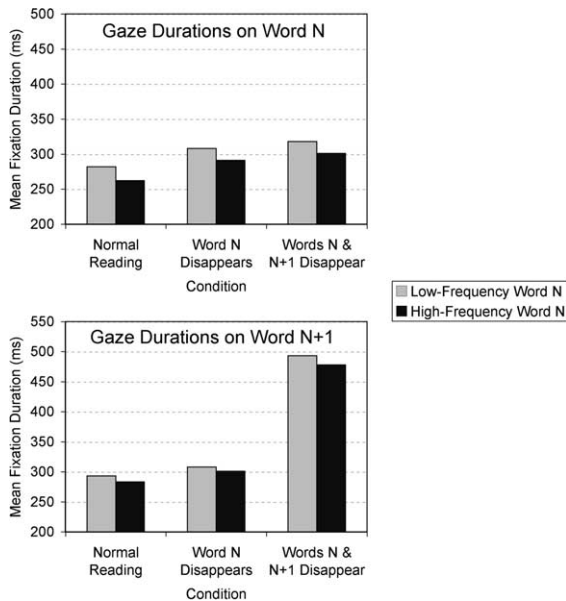


Fig. 8. Simulated results of the Rayner et al. (2004) disappearing-text paradigm. The top panel shows the gaze durations on word  $n$  as a function of its frequency (high = 105 per million vs. low = 1 per million) and the three display-change conditions: (1) no display change (i.e., normal reading); (2) word  $n$  disappears after 60 ms; (3) both word  $n$  and word  $n + 1$  disappear after 60 ms. The bottom panel shows the gaze durations on word  $n + 1$ , also as a function of word  $n$ 's frequency and the three display-change conditions.

frequency effect on the gaze duration on word  $n$  is evident in all three display-change conditions (which was the observed result, suggesting that the brief display interval was sufficient for normal lexical processing of word  $n$ ). The second is that the gaze durations on word  $n$  only increased modestly in the two display-change conditions. The third is that the gaze durations on word  $n + 1$  were much larger in the condition where words  $n$  and  $n + 1$  disappeared than in the other two conditions. We interpret these trends as showing that the condition in which both words  $n$  and  $n + 1$  disappear is much more disruptive to reading than the condition in which only word  $n$  disappears. This conclusion is also supported by the fact that, in both of the display-change conditions, the model shifted attention to word  $n$  after it had already disappeared approximately 15% of time. (These trials reflect saccadic error; the eyes are directed towards word  $n - 1$  but overshoot their target, landing on word  $n$  and prematurely triggering the “clock” to make that word disappear.) In contrast, the model shifted attention to word  $n + 1$  after it had already disappeared approximately 76% of the time. Thus, there is a much higher probability of the model shifting attention to a word that has already disappeared when both word  $n$  and word  $n + 1$  disappear than when only word  $n$  disappears. This discrepancy in how frequently the model encounters a missing word and must wait for the saccade deadline means that the former condition will be much more disruptive to normal reading than the later.

Our simulation thus suggests one interpretation of the Rayner et al. (2005) results: 50–60 ms is sufficient for the visual information about a word to initiate lexical processing of that word, but only if attention has also been allocated to the word. By this account, attention is an ingredient that is necessary to “fix” the information that is available from visual processing into a more stable representational format (e.g., orthographic codes). The reason why the disappearance of both word  $n$  and word  $n + 1$  is so disruptive is that, attention shifts from word  $n$  to word  $n + 1$  after word  $n + 1$  has already disappeared most of the time. When this happens, it is impossible to do any lexical processing on word  $n + 1$ . If this account is correct, then it suggests that the Rayner et al. (2005) results will be problematic for models of eye-movement control that posit the parallel allocation of attention. This prediction is based on the fact that, according to these models, attention will most often be allocated to both word  $n$  and word  $n + 1$  simultaneously, so that any observable difference in overall reading rate between the two display-change conditions in the Rayner et al. (2005) experiment should be minimal. This prediction requires evidence from future research. We will now turn to the issue of how our model has been used to guide new research.

## 5. Other research motivated by *E-Z Reader*

Our primary goal in developing the *E-Z Reader* model has been to provide a conceptual framework for thinking about how cognition might guide the eyes during reading. As we have tried to make clear in all of our previous articles, our model does not provide a “deep” explanation of any of the processes that are thought to mediate eye-movement control; it instead describes how these processes interact across time to determine when and where the eyes move during reading. We would argue that our efforts have been successful as witnessed by the number of models that have been proposed as alternatives to ours, and by the amount of new research that our model has motivated. This special issue already provides an overview of the models that have been developed in response to ours (see also Reichle et al., 2003), so in this final section, we will briefly review some of the research that has been motivated by our model.

### 5.1. Morphological processing

One example of how the model has been used to explore issues related to lexical processing was reported by Pollatsek, Reichle, and Rayner (2003). The *E-Z Reader* model was used in a series of simulations to evaluate the explanatory adequacy of two alternative views of how morphemically complex words are identified during reading: a “horse race” model in which individual morphemes and whole-word units are processed in parallel, and a serial-integration model in which individual morphemes are first identified and then combined into larger units of meaning.

This work was motivated by several experiments in which both the length and frequency of Finnish compound words and their first and second constituents were orthogonally manipulated (Hyönä & Pollatsek, 1998; Pollatsek, Hyönä, & Bertram, 2000). These experiments revealed systematic effects of the properties of both the whole words and their constituents, with the effects of the first constituents appearing earlier than those of the whole word or second constituents. Although these results were originally interpreted as being consistent with a model in which both whole words and their constituents are processed in parallel (i.e., the horse-race model), the simulation that actually provided the best account of the results was one that incorporated the key assumptions of the serial-integration model – that first and second constituents are first identified in turn, and then integrated to give the meaning of the whole word. Although these results are preliminary, they illustrate how other theoretical assumptions (e.g., assumptions about morphological processing) can be embedded in the framework of our model so as to evaluate how well these assumptions account for data collected in eye-tracking experiments. This approach has also been used to evaluate various theoretical assumptions about how lexical ambiguity is resolved during reading (see Reichle et al., 2003; Reichle, Pollatsek, & Rayner, 2005).

### 5.2. Word frequency and predictability

The original versions of *E-Z Reader* used an alternative version of Eq. (1) – one in which the effects of a word's frequency and predictability were combined in a multiplicative manner to give the duration of  $L_1$ . Although this model was able to explain both frequency and predictability effects, it could not explain the results of an experiment in which the frequency and predictability of specific target words were orthogonally manipulated (Rayner et al., 2004). In this experiment, the effects of frequency and predictability combined in an additive manner on the fixation durations, but influenced the skipping rates in an interactive manner, but opposite in direction to the interaction in processing time assumed in the multiplicative model (i.e., high-frequency predictable words were skipped more often than words in the other three conditions).<sup>7</sup> The failure of the multiplicative version of *E-Z Reader* to explain these results motivated the current formulation of our model, where a word's frequency and predictability are combined in an additive manner (see Eq. (1)). We expect that these types of refinements will continue to be necessary as more is learned about the relationship between lexical variables and how they affect the eye movements of readers. For example, future ver-

sions of *E-Z Reader* may incorporate variables other than just word frequency and predictability (e.g., age of acquisition; see Footnote 4).

### 5.3. The vision–mind interface

We (Pollatsek et al., 2005) recently completed several simulations to examine the interface between visual processing, on the one hand, and attention and lexical processing, on the other. Some of these simulations were of experiments involving display-change paradigms, and were briefly described in the preceding section of this paper. Another pair of simulations that were not reported evaluated two assumptions about how visual information is integrated across saccades and whether or not lexical processing continues during eye movements. The results of these simulations were informative in that an assumption that seemed reasonable (e.g., that lexical processing halts until the visual information from the current viewing location reaches the brain) led to some unexpected and problematic results – bi-modal fixation-duration distributions. These simulations led us to formulate the assumptions of our current model: that lexical processing continues during saccades, using whatever visual information was made available from the previous viewing location until the information from the new viewing location becomes available. We believe that these conclusions are general and that the principles that were suggested by our simulations may be applicable to tasks other than reading (e.g., scene perception).

### 5.4. The $L_1$ vs. $L_2$ distinction

In Reingold's (2003) response to our *Behavioral and Brain Sciences* paper (Reichle et al., 2003), he noted that one prediction that falls out of the distinction between  $L_1$  and  $L_2$  is that some variables might be expected to primarily affect  $L_1$ , and hence affect first-fixation durations, whereas other variables might be expected to primarily affect  $L_2$ , and hence the amount of spillover that is observed. As was already mentioned, Reingold and Rayner (2005) tested this prediction by having readers read sentences that contained a target word that was either printed normally, in alternating or in faint print. Interesting differences emerged across the conditions so that, for example, a word printed in alternating or faint print yielded longer fixations on the target word, but there were no real differences in the size of the spillover effects. These results are consistent with one interpretation of the  $L_1$  vs.  $L_2$  distinction – that variables that influence stimulus quality should affect first-fixation durations (which are largely a function of the time needed to complete  $L_1$ ), but should not affect the duration of the spillover (which reflects the difference between the saccadic latency and the amount of time that is needed to complete  $L_2$ ; see Fig. 2).

<sup>7</sup> This pattern of results has recently been replicated in an experiment involving native French readers and target words embedded in short passages (Miellet, 2004, personal communication).

### 5.5. The emergence of adaptive eye-movement control

One important but largely ignored question is: How do readers learn to control their eye movements during reading? As has been noted throughout this paper and elsewhere (see Rayner, 1998), although the eye-movements of skilled readers exhibit a large degree of variability, many of the basic characteristics of readers' eye movements (e.g., the "benchmark" phenomena simulated in the first part of this article) are also remarkably systematic and presumably allow readers to move their eyes in a way that makes the task of reading as efficient as possible. Unfortunately, existing models of eye-movement control (including ours) are limited in that they only provide descriptions of the cognitive and/or oculomotor processes that guide the eye movements of skilled readers; none of the existing models explain how this skilled behavior actually develops or is learned.

To address this issue, Reichle and Laurent (2005) examined the eye-movement behavior of an adaptive reading "agent" that was given the task of learning how to move its eyes (via a reinforcement-learning algorithm; Barto, 1995) so as to read as efficiently as possible. Like human readers, the agent was subject to several hard constraints, such as limited visual acuity, minimal saccadic programming and word identification latencies, and saccadic error. The agent was also only allowed to process one word at a time (i.e., attention was assumed to be serial). Under these constraints, the adaptive agent learned to move its eyes in a manner that resembled the eye movements of human readers: The agent directed its saccades towards the middle of words, looked at difficult-to-process words longer than easier words, and showed both a tendency to skip easy words and a tendency to refixate difficult words. Perhaps the most interesting behavior that emerged from the agent was that it learned to initiate a saccadic program to move the eyes from word  $n$  to word  $n + 1$  before word  $n$  has been completely identified. This behavior was evidently a compromise between fixating each word until it was completely identified (which would have resulted in long fixations and a slow overall reading rate) and initiating a saccade from word  $n$  to word  $n + 1$  as soon as lexical processing of word  $n$  began (which would have resulted in the eyes leaving word  $n$  before it had been completely identified, leading to slower lexical processing and/or frequent regressions, and an overall slower reading rate).

There are two important implications of the adaptive reading agent's behavior. The first is that it suggests that skilled readers, through years of extensive practice, learn to use rapidly available lexical information about words to make their "decisions" about when to move their eyes from one word to the next. This behavior is consistent with something like a familiarity check, and may provide one account of how it develops in skilled readers. The second implication of the agent's behavior is

the simple fact that its decisions about when to move its eyes reflect on-going lexical processing. In other words, the moment-to-moment decisions about when to move the eyes are made on the basis of how much processing has been completed on the currently attended word. This behavior also contradicts what might have been predicted according to some models of eye-movement control (Suppes, 1990, 1994; and to a lesser degree Engbert, Longtin, & Kliegl, 2002; and Reilly & Radach, 2003) – that the agent would simply learn to move its eyes forward at a more-or-less fixed interval (with lexical processing having little or no bearing on the initiation of saccadic programs), so as to maintain some minimal constant reading rate. We therefore consider the sum total of these simulation results as being consistent with many of the core assumptions of the *E-Z Reader* model. Moreover, these simulations provide one explanation for how the assumptions of our model might develop in skilled readers.

### 5.6. Physiological evidence for the eye-mind link?

In our *Behavioral and Brain Sciences* paper (Reichle et al., 2003), we introduced a tentative mapping between the functional components of the *E-Z Reader* model and several cortical and sub-cortical brain structures that are thought to support reading. This mapping was admittedly very speculative and was based largely on the results of existing brain-imaging experiments. A more direct test of this mapping comes from a recent *event-related potential* (ERP) experiment (Reichle, Tokowicz, Liu, & Perfetti, 2005) that was designed to evaluate a core assumption of the *E-Z Reader* model – that an early stage of word identification is the "engine" that drives eye movements from one word to the next. To test this prediction, a paradigm was developed in which participants rapidly moved their eyes from a centrally displayed letter string to a peripheral letter string and rapidly decided whether either of the strings was a non-word. The critical manipulation was whether the center letter string was a high- or low-frequency word. (During most of the trials, both of the letter strings were real words.)

Participants' saccades were identified in the ERP data using the deflections recorded in the outer canthi of the eyes (using an algorithm developed by Csibra, Johnson, & Tucker, 1997). The task was then simulated using *E-Z Reader* to generate predictions about the time course of lexical processing of the center word and the onset of the saccade from this word to the peripheral letter string. These predictions guided subsequent analyses of the ERP data. The critical analysis showed an ERP component that was reliably modulated by the frequency of the center word in the left and central posterior parietal channels. This component occurred at that point in time when *E-Z Reader* predicted that the familiarity check on the center word should have been completed.

A source localization algorithm (LORETA) also indicated that this component most likely originated from the left extrastriate cortex and left fusiform gyrus – the classic “word-form” areas that are widely thought to be responsible for orthographic processing (McCandliss, Cohen, & Dehaene, 2003). This result is consistent with the tentative mapping that was presented in our *Behavioral and Brain Sciences* paper (Reichle et al., 2003) and provides some additional support for our model’s assumption that an early stage of (possibly form-based) lexical processing is the engine driving eye movements during reading. This result also supports our assertion that this mapping – although still tentative – is nevertheless well enough specified to be useful in guiding new research.

## 6. General discussion

This completes our survey of the *E–Z* Reader model. As we have argued elsewhere (Rayner, Liversedge et al., 2003), our model explains a considerable amount of eye-tracking data, including the data from at least two corpora of English sentences (Rayner et al., 2004; Schilling et al., 1998) and one corpus of short French paragraphs (Sparrow, Mielle, & Coello, 2003). Although critics of the model may argue that some of its assumptions are unfounded, we would counter that we have tried to incorporate principles that are generally applicable and widely accepted in the literature (e.g., the assumption that attention is needed to “bind” the features of visual objects into unified representations; Treisman & Gelade, 1980; Treisman & Souther, 1986; Wheeler & Treisman, 2002; Wolfe, 1994; Wolfe & Bennett, 1996). We also believe that our recent successes in simulating the results of gaze-contingent paradigms indicate that our estimates of the key model parameters are quite accurate. With earlier versions of our model, we tended to use rather extreme parameter values in order to be overly conservative and thereby counter any claim that our model’s performance was dependent upon process durations that were too short to be plausible. In contrast, the parameter values of our current model are serious estimates of the time that it takes to complete key processes (e.g., lexical processing, the programming of eye movements, etc.).

More generally, we believe that the *E–Z* Reader model provides a relatively transparent theoretical framework for thinking about the relationship between cognition, on the one hand, and eye-movement behavior, on the other. This framework has already proven itself to be useful. The model has been used to generate novel predictions (some of which have already been confirmed; e.g., the cost associated with skipping words; Kliegl & Engbert, 2005; Pollatsek et al., 1986; Pynte et al., 2004; Rayner et al., 2004) and it has inspired quite a bit of new research (some of which was discussed in the previous section of this paper).

Despite these successes, we do acknowledge that many of the specific details of our model may still be underspecified or simply incorrect. For example, we have already noted that the model does not provide a deep explanation of any of the processes that guide eye movements during reading (e.g., our model does not provide a detailed account of word identification); the model instead describes the relationships among these processes and how their interactions determine when and where the eyes move during reading. To take another example, one area of residual ignorance concerns refixations; in our model, words are the recipients of multiple fixations because of saccadic error and because of our assumption regarding corrective refixation saccades (see Eq. (6)). We would be surprised if this last assumption did not change in the next few years as we learn more about the determinants of refixations. This should in turn allow us to more fully understand many of the other issues that we have examined using our model; for example, a more precise understanding of what causes refixations may make it easier to evaluate assumptions regarding the identification of morphemically complex words (Pollatsek et al., 2000).

Finally, we would like to point out that the various models of eye-movement control that have been proposed as alternatives to ours and that are described in this special issue will also provide useful points of contrast for generating new predictions and guiding new research. Ten years ago, the then current models of eye-movements control were divided into two camps: those that posited an eye-mind link (cognitive-control models) and those that did not (oculomotor models). The debate back then focused almost exclusively on the issue of whether or not cognitive events (e.g., word identification) were linked to the moment-to-moment decisions about when to move the eyes. Today’s models provide a more complete account of eye-movement control during reading and thus suggest alternative dimensions along which the models might be evaluated. One such dimension that has already been mentioned several places in this article is whether attention is allocated serially or in parallel. We suspect that as the different models of eye-movement control continue to become more refined, our ability to both ask interesting questions and to make finer-grained distinctions among the models will also continue to improve. We therefore believe that the models still hold tremendous promise for guiding future research.

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## Appendix

The following table shows all of the *E-Z* Reader 9 parameters, their values, and short descriptions their interpretations

Model component	Parameter	Value	Interpretation
Visual processing	$V$	50	Eye-to-brain lag (ms)
	$\varepsilon$	1.15	Effect of visual acuity on $L_1$
Lexical processing	$\alpha_1$	122	Mean maximum $L_1$ processing time (ms)
	$\alpha_2$	4	Effect of frequency on $L_1$ processing time (ms)
	$\alpha_3$	10	Effect of predictability on $L_1$ processing time (ms)
	$\Delta$	.5	Proportional difference between $L_1$ and $L_2$
	$\sigma_\gamma$	.22	Standard deviation of gamma distributions (i.e., $\sigma = .22 \mu$ )
Saccadic programming	$M_1$	100	Mean labile programming time (ms)
	$\xi$	.5	Proportion of $t(M_1)$ allocated to “engaging oculomotor system”
	$M_2$	25	Mean non-labile programming time (ms)
	$R$	117	Mean refixation “decision” time (ms)
	$S$	25	Saccade duration (ms)
	$\Psi$	7	Optimal saccade length (character spaces)
	$\Omega_1$	7.3	Effect of launch-site fixation duration on systematic range error
	$\Omega_2$	3	Effect of launch-site fixation duration on systematic range error
	$\eta_1$	.5	Saccade random error component (character spaces)
	$\eta_2$	.15	Saccade random error component (character spaces)
	$\lambda$	.09	Increase in refixation probability per character space deviation from word center

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