Published in final edited form as:
Vis cogn. 2012 January 1; 20(4-5): 360–390. doi:10.1080/13506285.2012.667006.

Eye movements in reading versus nonreading tasks: Using E-Z Reader to understand the role of word/stimulus familiarity

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Abstract

In this article, we extend our previous work (Reichle, Pollatsek, & Rayner, 2012) using the principles of the E-Z Reader model to examine the factors that determine when and where the eyes move in both reading and non-reading tasks, and in particular the role that word/stimulus familiarity plays in determining when the eyes move from one word/stimulus to the next. In doing this, we first provide a brief overview of E-Z Reader, including its assumption that word familiarity is the "engine" driving eye movements during reading. We then review the theoretical considerations that motivated this assumption, as well as recent empirical evidence supporting its validity. We also report the results of three new simulations that were intended to demonstrate the utility of the familiarity check in three tasks: (1) reading; (2) searching for a target word in embedded in text; and (3) searching for the letter *O* in linear arrays of Landolt *C*s. The results of these simulations suggest that the familiarity check always improves task efficiency by speeding its rate of performance. We provide several arguments as to why this conclusion is not likely to be true for the two non-reading tasks, and in the final section of the paper, we provide a fourth simulation to test the hypothesis that problems associated with the mis-identification of words may also curtail the too liberal use of word familiarity.

As illustrated by this special issue, there have been several recent efforts to develop computational models that explain how the mind influences the patterns of eye movements that are observed when humans perform various visual-cognitive tasks (e.g., trying to locate a vehicle in a landscape, Zelinsky, 2008; see also Itti & Koch, 2000; Nuthmann, Smith, Engbert, & Henderson, 2010; Torralba, Oliva, Castelhano, & Henderson, 2006). Although these models provide detailed accounts of a number of different phenomena, they have been limited in scope because they either explain the timing of eye movements (i.e., fixation durations) or the patterns of where the eyes move (i.e., fixation locations), but not both. With one notable exception (Salvucci, 2001)[1], these models have also been silent about a second important issue—whether or not a single set of theoretical assumptions can explain eye-movement behavior across a range of visual-cognitive tasks (e.g., reading, visual search, scene viewing, etc.; for a discussion of these issues, see Nuthmann & Engbert, 2009). However, as is evidenced by this special issue, there is an increasing awareness of these

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[1] Salvucci (2001) used the EMMA model to simulate patterns of eye movements observed during reading, equation solving, and driving. Because this model is implemented within the more general framework of the *ACT-R* cognitive architecture (Anderson & Lebiere, 1998), it provides a single set of assumptions for explaining eye-movement control in a variety of visual-cognitive tasks.

important theoretical issues, as well as recent attempts to explain eye movements during both reading and non-reading tasks (Reichle, Pollastsek, & Rayner, 2012). For example, Nuthmann and Henderson (this volume) have demonstrated that the *CRISP* model (Nuthmann et al., 2010) can simulate fixation durations during both reading and scene viewing, and on this basis of this, have argued that eye movements in these markedly different tasks can be explained using a single theoretical framework in which saccadic programming is only loosely coupled to cognition.

Our recent attempts to address these issues have involved a different approach in that we have used an existing computational model of eye movements in reading, *E-Z Reader*, as a framework to examine the assumptions that are necessary to account for eye movements in non-reading tasks (Reichle et al., 2012). This article extends this work by more carefully examining one of the model's core assumptions about how the mind "decides" when to move the eyes: that the rapid assessment of a word's or stimulus' familiarity provides a reliable "trigger" for initiating a saccadic program to the next word/stimulus. Our goal is to elucidate the possible mechanisms that determine when the eyes move during reading and during other, non-reading, visual-cognitive tasks.

The E-Z Reader model actually consists of a "family" of models that have been developed over the past decade to provide increasingly comprehensive and accurate accounts of the patterns of eye movements that are observed in reading (Pollatsek, Reichle, & Rayner, 2006; Rayner, Ashby, Pollatsek, & Reichle, 2004; Rayner, Li, & Pollatsek, 2007; Rayner, Reichle, Stroud, Williams, & Pollatsek, 2006; Reichle, Pollatsek, Fisher, & Rayner, 1998; Reichle, Rayner, & Pollatsek, 1999, 2003; Reichle, Warren, & McConnell, 2009; for a review, see Reichle, 2011) and more recently, a variety of other non-reading tasks (e.g., visual search; Reichle et al., 2012). In the context of explaining eye movements during reading, all of the versions of the model have maintained two basic theoretical assumptions: (1) attention to support lexical processing is allocated in a strictly serial manner, so that only one word at a time is being processed lexically, and (2) the signal to begin programming a saccade to move the eyes from one word to the next is the completion of a preliminary stage of lexical processing called the *familiarity check* (labeled "L_1" in the formalism of the models).

Much more will be said below about this preliminary stage because our goal in this article is to provide a more detailed account of the functional role that it would play in reading and other visual-cognitive tasks. However, it is important to note that, in the context of explaining eye movements during these other tasks, the E-Z Reader model maintains its assumption about the serial allocation of attention (i.e., only one object is processed and identified at a time) but relaxes the assumption that this preliminary familiarity check stage is necessarily the trigger for an eye movement to the next word or object. As a result, the signal to initiate saccadic program in non-reading tasks may correspond to something other than an early stage of lexical identification, or in the context on non-reading tasks, object identification up to the level needed to perform the task (e.g., determining whether the attended stimulus is or contains the target). For example, in scanning text for the occurrences of a specific target word (e.g., Rayner & Fischer, 1996), the signal to move the eyes may correspond to some minimal deadline that is sufficient to allow the extraction of visual information, whereas in a more complex visual search (e.g., Williams & Pollatsek, 2007), the signal to move the eyes may correspond to the full identification of whatever stimulus is being processed[2].

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[2] For further discussion of the saccadic-programming deadline hypothesis, see Engbert and Kliegl (2001) and Henderson and Ferreira (1990).

Our goals in this article are three-fold. The first is to demonstrate via simulations that the familiarity check actually allows the reader to progress through text more efficiently than if the reader waited for full identification of the attended stimulus to program an eye movement. The second is to use the simulations to examine the conditions under which the familiarity check facilitates the performance of non-reading tasks. As already stated, the familiarity check seems to be limited to reading (and perhaps other reading-like tasks), and consequently it is important to understand the boundary conditions under which the familiarity check might be expected to be used instead of other "triggers" for initiating saccadic programming. By doing this, we thus intend to accomplish our third goal of providing a more general statement about the nature of the relationship between the eyes and the mind and—a bit more specifically—the nature of the "decision" about when to move the eyes in reading versus other visual-cognitive tasks. Before doing this, however, it is first necessary to provide a brief overview of the E-Z Reader model and some discussion of the familiarity check, including the factors that motivated it, how it affords efficient reading, and the empirical evidence that is consistent with its existence and use during reading. The next two sections are devoted to these issues.

The E-Z Reader Model

This overview of the E-Z Reader model will first describe how the model has been used to explain eye movements during reading, and then indicate how the model's assumptions have been adjusted to explain eye movements in other visual-cognitive tasks. (As will become evident, these adjustments are very minor, mostly amounting to changing the model's parameter values.) For a detailed description of the model, see Reichle (2011) or Reichle et al. (2012). Figure 1 is a schematic diagram of the model.

As Figure 1 shows, processing begins with a pre-attentive stage of visual processing (labeled V in the figure). This stage is pre-attentive in the sense that information is processed in parallel from across the entire visual field, irrespective of what is being attended; however, the information extracted respects the known limitations of visual acuity. According to the model, this early stage of processing takes 50 ms to complete (i.e., $V = 50$ ms), consistent with empirical estimates of the "eye-to-mind lag" (Clark, Fan, & Hillyard, 1995; Foxe & Simpson, 2002; Mouchetant-Rostaing et al., 2000; Van Rullen & Thorpe, 2001). (For a complete list of the model's parameters, their interpretations, and their default values, see Table 1.) The pre-attentive visual stage also makes two types of information available for further processing. The first is the low spatial-frequency information corresponding to word boundaries, etc. that is used to select the targets of upcoming saccades; the second is the high spatial-frequency information corresponding to the fine-grained orthographic details (e.g., letter features) that are necessary for lexical processing.

Lexical processing is completed in two successive stages: A preliminary stage called the familiarity check or L_1, followed by a later stage called the completion of lexical access or L_2. We are going to be a bit vague about what the completion of L_1 actually corresponds to right now because it is discussed at length in the next section of the article; however, the completion of the L_2 stage corresponds to traditional conceptualizations of lexical access, wherein the meaning of a word has been activated and is available for further linguistic processing.

The time required (in ms) to complete the familiarity check on word n, $t(L_1)$ is set equal to 0 ms with a probability equal to $pred_n$, or word n's within-sentence predictability, which is operationally defined using the proportion of subjects who correctly guess word n when they are allowed to read words 1 through n-1 (Taylor, 1953). This assumption reflects the fact that words are occasionally guessed from their context (e.g., predictable function words are sometimes never fixated, even under artificial viewing conditions where each word has be fixated in order to be seen; Rayner, Well, Pollatsek, & Bertera, 1982). However, in the majority of cases, $t(L_1)$ is specified by Equation 1:

$$t(L_1)=\alpha_1-\alpha_2\ln(freq_n)-\alpha_3 pred_n \quad (1)$$

In Equation 1, $freq_n$ is word n's frequency of occurrence in printed text (i.e., its number of occurrences per million words; e.g., Francis & Kucera, 1982) and the free parameters α_1 (= 104), α_2 (= 3.5), and α_3 (= 19) determined the mean time to complete L_1 for word n, and how this time is attenuated by word n's frequency and predictability. Equation 1 gives the mean time because the actual time to complete L_1 during any given Monte-Carlo simulation is a random deviate that is sampled from a gamma distribution with $\sigma = 0.22\ t(L_1)$. This value is then adjusted using Equation 2 to simulate the slowing effect that limited visual acuity has on the time required to complete the familiarity check:

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

In Equation 2, ε (= 1.15) is a free parameter that determines the degree to which the mean absolute distance between each of the N letters (indexed by i) of the word that is being processed and the current fixation location, *fixation*. Thus, using Equations 1 and 2, words that are frequent, predictable, short in length, and/or close to the center of vision (i.e., the current fixation) will be processed more rapidly than words that are infrequent, unpredictable, long, and/or far from the center of vision; this is in agreement with what is observed in reading data (for reviews, see Rayner, 1998, 2009; Schotter, Angele, & Rayner, 2012).

The mean time required for the completion of lexical access, $t(L_2)$, is specified by Equation 3, where Δ (= 0.34) is a free parameter that causes $t(L_2)$ to be some fixed proportion of $t(L_1)$, with the latter being specified by Equation 1 (i.e., prior to being stochastically realized as a random deviate whose value is then modulated by Equation 2). As with $t(L_1)$, the actual value of $t(L_2)$ during any Monte-Carlo simulation is sampled from a gamma distribution with $\sigma = 0.22\ t(L_2)$. However, in contrast to $t(L_1)$, the duration must be greater than 0 ms because even the meanings of "guessed" words have to be activated in memory, and this activation takes time. Also, because this entails activation of semantic-based lexical codes, $t(L_2)$ is not modulated by visual acuity, contrary to $t(L_1)$.

$$t(L_2)=\Delta\left[\alpha_1-\alpha_2\ln(freq_n)-\alpha_3 pred_n\right] \quad (3)$$

As Figure 1 shows, the completion of L_1 on word n causes the initiation of a saccadic program to move the eyes to word n+1. L_2 then continues to completion, which then causes attention (labeled A in Fig. 1) to shift to the next word and the initiation of some minimal amount of post-lexical processing (i.e., integration, which is labeled I in Fig. 1) of word n. The time required to shift attention, $t(A)$, is sampled from a gamma distribution with μ = 25 ms and $\sigma = 0.22\ t(A)$. Likewise, the time required to complete integration, $t(I)$, is sampled from a gamma distribution with μ = 25 ms and $\sigma = 0.22\ t(I)$. The latter might correspond to whatever processing is "good enough" (Ferreira, Bailey, & Ferraro, 2002; Ferreira & Patson, 2007; Swets, Desnet, Clifton, & Ferreira, 2008) to avoid interrupting the forward progression of the eyes and attention through the text, and thus reflects whatever minimal post-lexical processing is necessary to ensure that further higher-level comprehension of whatever is being read is likely to continue without difficulty. Viewed is this way, the completion of integration is like a signal to “not step on the brakes,” in contrast to the familiarity check which is like a signal to “step on the gas.”

As one might guess, however, integration can and occasionally does fail in two different ways. The first occurs whenever the integration of word n fails to complete before word n+1 has been identified; in such cases, the eyes and attention are drawn back to the source of integration difficulty so that integration does not lag too far behind lexical processing. The second occurs with some probability that is determined by the free parameter p_F (= 0.01) that is meant to be a proxy for the types of failures in higher-level language processing (e.g., mis-parsing of syntactically ambiguous sentences; Frazier & Rayner, 1982; Frazier, Carlson, & Rayner, 1983). (This assumption is a proxy because the E-Z Reader model currently does not provide any detailed account of higher-level language processing, but only how failure in such processing affect the movement of the eyes and attention; see Reichle, 2012). With either type of integration failure, the eyes and attention are drawn back to the source of integration difficulty, word n, with probability p_N (= 0.5) and to some earlier location in the text (e.g., word n-1) with probability $1 - p_N$. (Again, this last assumption is meant to be a proxy for a more detailed account of how the eyes are directed back to different sources of integration failure in the service of repairing those failures.)

The model assumptions that have been described thus far specify how readers decide when to move their eyes. The remaining model assumptions largely concern saccadic programming and execution and are thus related to how readers decide where to move their eyes. Because there is a considerable amount of evidence that the “when?” and “where?” decisions are made independently (e.g., Rayner & McConkie, 1976; Rayner & Pollatsek, 1981), and because the focus of this article is on the familiarity check and its role is deciding when the eyes move, the remaining model assumptions will be described very briefly. (For a more detailed description of the assumptions and their motivation, see Reichle, 2011, or Reichle et al., 2012).

As Figure 1 shows, saccade programming is completed in two stages: an initial labile stage, M_1, in which the program is canceled if another saccadic program is initiated, followed by a non-labile stage, M_2, that is not subject to cancelation. This distinction between M_1 and M_2 was motivated by the results of “double-step” experiments (e.g., Becker & Jürgens, 1979) which demonstrated that a saccade to a specific target location could be canceled if information about a second target location was presented prior to some “point of no return” corresponding to the beginning on the non-labile stage. In the model, the mean times (in ms) required to complete these two stages of programming are sampled from gamma distributions with $t(M_1)$ = 125 ms and $t(M_2)$ = 25 ms, and $\sigma = 0.22\ \mu$, respectively. (The labile stage of regressive saccades requires an additional 30 ms to complete in accordance with findings that inhibition of return often slows regressive saccades; e.g., Rayner, Juhasz, Ashby, & Clifton, 2003.) Finally, the actual saccades require a constant 25 ms to execute. (This last assumption is a simplification because the saccade durations actually increase with saccade length; Fuchs, 1971; Rayner & Morrison, 1981.)

The primary saccades that move the eyes from one word to another are directed towards the *optimal-viewing location*, or center of the targeted word (O’Regan, 1981, 1990; O’Regan & Lévy-Schoen, 1987). The actual saccades often deviate from their intended target, however, because of both systematic and random motor error (McConkie, Kerr, Reddix, & Zola, 1988; McConkie, et al., 1991), as specified by Equation 4:

$$\textit{saccade length} = \textit{intended length} + \textit{systematic error} + \textit{random error} \qquad (4)$$

In Equation 4, the systematic error causes long saccades (i.e., saccades longer than 7 character spaces in English) to undershoot their intended targets, and short saccades (i.e., less than 7 character spaces) to overshoot their intended targets, as specified by Equation 5. In this equation, the free parameter Ψ (= 7) determines the saccade length that does not under- or overshoot its intended target, and the right-hand term specifies how this tendency is modulated by the prior fixation duration on saccade launch-site word, with the free parameters Ω_1 (= 6) and Ω_2 (= 3) causing a reduction of the systematic error for saccades following long fixations.

$$\textit{systematic error} = (\Psi - \textit{intended length})\,\{[\Omega_1 - \ln(\textit{fixation duration})]/\Omega_2\} \tag{5}$$

The random motor error component is sampled from a Gaussian distribution with μ = 0 character spaces and σ (in character spaces) specified by Equation 6. There, η_1 (= 0.5) and η_2 (= 0.15) are free parameters that cause the random error to increase with the length of the intended saccade.

$$\sigma = \eta_1 + (\eta_2\ \textit{intended length}) \tag{6}$$

The last assumption of the E-Z Reader model does not concern the primary saccades that move the eyes from one word to the next, but corrective saccades that move the eyes from one (usually poor) viewing location on a word to another (usually better) viewing location on the same word. The decision to make these corrective saccades is determined probabilistically, as specified by Equation 7. As the equation indicates, this decision is made using information provided by an efference copy (Carpenter, 2000; see also Engbert, Nuthmann, Richter, & Kliegl, 2005; Nuthmann, Engbert, & Kliegl, 2005) of the primary saccade to determine the error or distance (in character spaces) between the initial fixation location and the center of the word being processed (O'Regan, 1981; O'Regan & Lévy-Schoen, 1987).

$$p = \max(\lambda|\textit{fixation} - \textit{OVP}|, 1) \tag{7}$$

The above assumptions regarding saccadic programming and execution allow the model to simulate several important aspects of where the eyes move during reading: that the fixation landing-site distributions are centered on the words but are normally distributed, with missing tails reflecting instances where the eyes under/overshot their intended targets, and with the variability of the distribution increasing with saccade length and decreasing with the launch-site fixation duration (McConkie et al., 1988, 1991; O'Regan, 1990; Rayner, 1979; Rayner, Sereno, & Raney, 1996). As indicated above, however, the primary focus of this article is the E-Z Reader model's assumption about the familiarity check and how this early stage of processing influences the moment-to-moment decisions about *when* to move the eyes. Thus, we will now shift our discussion from how the model specifies *where* the eyes move to consider the "when?" decision in more depth.

The Familiarity Check

Theoretical Motivation

The original impetus for positing the familiarity check in the E-Z Reader model is that it provided a plausible mechanism to explain how something as sluggish as lexical processing could initiate saccadic programming soon enough to give rise to fixation durations that, on average, tend to be very short (e.g., 200–250 ms; e.g., Schilling, Rayner, & Chumbley, 1998). That is, by allowing an early stage of lexical processing to be the "trigger" to initiate saccade programming, the model provided an account of how cognition could intervene rapidly enough to "decide" when the eyes move from one word to the next. And by making this decision a function of various lexical variables (e.g., word frequency, predictability, length, etc.), one could explain how the time required to make these decisions affected the durations of individual fixations, thereby explaining how variables affect fixation durations during reading (for a review, see Rayner & Pollatsek, 1989; Rayner, Pollatsek, Ashby, & Clifton, 2012).

The specific manner in which the familiarity check was implemented in E-Z Reader and how its time course related to both the completion of lexical access and saccadic programming (see Equations 1–3) also allowed the model to explain several other phenomena related to eye movements in reading. As Figure 2 shows, because the added time required to complete lexical access is a fixed proportion of the time required to complete the familiarity check, and because the time required to complete saccadic programming is a constant, the time that is available for parafoveal processing of word $n+1$ from word n will vary as a function of the time required to complete the familiarity check on word n.

As Figure 2 shows, this effectively means that, as word n becomes more difficult to process, less time is available for the parafoveal processing of word $n+1$. There are two important ramifications of this fact. The first is that a difficult-to-process (e.g., low frequency) word will allow less parafoveal processing of the upcoming word, slowing its identification and consequently inflating the fixation duration on that word. This allows the model to explain *spillover effects*, or the finding that processing difficulty associated with one word can often "spill over" onto the next word (e.g., Rayner & Duffy, 1986). The second ramification of how the model explains parafoveal preview is that it allows the model to naturally explain the interaction between foveal processing "load" (i.e., the processing difficulty associated with the fixated word) and the amount of processing that is completed on the parafoveal word. For example, a difficult-to-process word typically allows less parafoveal processing of the next word (Henderson & Ferreira, 1990). The fact that E-Z Reader's familiarity-check assumption allowed the model to explain spillover, parafoveal preview, and how preview interacts with foveal load thus provided some additional justification for the assumption.

Subsequent simulations using E-Z Reader further suggested the necessity of the model's familiarity check assumption (Pollatsek et al., 2006). In these simulations, the model was used to simulate the results of gaze-contingent experiments called the boundary paradigm (Rayner, 1975). In these experiments, the letters of a target word are, in some conditions, replaced with random letters or *X*'s until the reader's eyes cross an invisible boundary located in the blank space immediate to the left of the word. This manipulation typically inflates the time spent looking at the target word by 40–50 ms, indicating that this amount of lexical processing is normally completed from the parafovea (i.e., from the word preceding the target word). Although E-Z Reader accurately predicted the size of this preview benefit, a variant of the model in which a single stage of lexical processing initiated saccadic programming at the same time that the shift of attention occurred (i.e., where the distinction between the L_1 and L_2 stages was eliminated) did not do as good of a job explaining the data. This result reveals one other possible limitation of single-stage models for reading (e.g., Morrison, 1984) and thereby provides an additional theoretical basis for including the familiarity-check assumption.

One final theoretical motivation for the familiarity check assumption comes from a series of more recent simulations that have been completed using artificial reading agents, or virtual entities that learn how to "read" as efficiently as possible (Liu & Reichle, 2010; Reichle & Laurent, 2006; Reichle, Liu, & Laurent, 2011). The agents are subject to a number of different psychological and physiological constraints that are known to delimit human performance during reading (e.g., visual acuity is limited, saccades take time to program and are subject to motor error, etc.), and, like humans, the agents must learn to move their eyes (and attention) to read efficiently without any explicit instruction about how to do so. The agents are capable of learning in this manner via reinforcement learning (Sutton & Barto, 1998) and are motivated to perform their task efficiently by being "rewarded" for each word that they identify and are "punished" for the time that they spend processing a sentence.

After training, the agents exhibit eye-movement behavior that is remarkably similar to that of human readers. For example, the agents direct their eyes towards the centers of words because the words can be more rapidly identified from that viewing location. One of the most important findings, however, is that the agents learn a heuristic very much like the posited familiarity check mechanisms in E-Z Reader. The agents do this by first learning the relationship between variables that are available to the agents (e.g., word length) and the time required to identify words. The agents then learn to exploit these relationships to anticipate the time required to identify individual words. In doing this, they also learn to initiate saccadic programming so that their eyes would leave a word right as that word was being identified. In other words, the agents use information at their disposal to learn how to fixate each word only as long as necessary—neither shorter nor longer than necessary. Had the fixations been any shorter, the agents' eyes would have moved too soon, resulting in, for example, the word being processed more slowly from poor viewing locations and thereby slowing the overall reading rate. And conversely, had the fixations been any longer, the fixations would have been unnecessarily long, also slowing the overall reading rate. The agents' strategy thus suggests that the familiarity check provides a "Goldilocks" solution for deciding when to move the eyes so that individual fixations are neither too short nor too long, but "just right." That being said, we will next examine the empirical evidence that is consistent with this possible solution.

Empirical Confirmation

One of the original motivations for the familiarity-check assumption is that it is consistent with theories of human memory (for a review, see Yonelinas, 2002) that posit that recognition performance is driven by two components—a rapidly available sense of familiarity, followed by a slower retrieval of information. This distinction is instantiated in Hintzman's (1984, 1988) *MINERVA 2* model and is readily explained using that model.

In this model, stimuli are encoded and represented in long-term memory as discrete memory traces, and a previously experienced stimulus can be recognized as such (e.g., as would be necessary to discriminate studied versus non-studied items in a recognition experiment) by probing long-term memory with either the stimulus or some subset of its features. This probing operation causes the traces in long-term memory to "resonate" to a degree that is concordant with the trace's similarity to the probe, and this resonance results in two distinct types of information. The first is called the *echo intensity* and simply reflects the overall amount to which the traces in long-term memory resonated in response to the probe. Because the echo intensity will (on average) be stronger for previously encountered stimuli than new stimuli, the value of the echo intensity can be used in conjunction with the basic principles of signal-detection theory as a basis for simulated recognition. The second type of information is called the *echo content* and corresponds to the retrieval of information; by probing long-term memory with some number of features, memory traces containing those features will resonate, generating a composite pattern of features that often "fills in" whatever features were originally associated with the features of the probe. Because the echo content provides a way of retrieving patterns of features from memory, it can be used to simulate the recall of information from memory.

For the present purposes, however, the important point to note is that the MINVERVA 2 model makes concrete the basic distinction between a rapidly available sense of familiarity and a slow retrieval of information. Furthermore, the model has been used to simulate human performance in a number of word-identification tasks (e.g., naming; Ans, Carbonnel, & Valdois, 1998). One of these models (Reichle & Perfetti, 2003; see also Reichle, 2012) has exploited the distinction between the echo intensity and echo content, arguing that the former may provide the signal to initiate saccadic programming during reading, while the latter corresponds to lexical access. By this conceptualization, the sense of familiarity that is provided by the echo intensity is the basis for the familiarity check in reading, whereas the pattern of orthographic, phonological, and semantic features that are made available from the echo content is the basis for lexical access.

Although the necessity of these two stages has been questioned for explaining the standard recognition memory task (in which subjects merely judge whether they have seen the stimulus before; e.g., see Rotello, Macmillan, & Reeder, 2004), the distinction seems quite a bit more reasonable for reading, where a quick judgment of familiarity may be the usual trigger to judge that the word is familiar, and that its meaning is soon likely to be available. However, then a second stage of actually encoding the word and possibly integrating it with the prior text (at least at some relatively superficial level) is needed to move attention and to encode and integrate the next word into the text. However, this is speculation. Is there any evidence for a mechanism that more closely corresponds to the familiarity check as posited in E-Z Reader? To date, there have been three experiments that were specifically designed to test the familiarity-check assumption.

The first of these experiments actually tested two assumptions of the familiarity check: (a) that it is an early stage of orthographic processing, and (b) that it can be dissociated from a subsequent stage of phonological and/or semantic processing (Reingold, 2003). To test this, Reingold and Rayner (2006) manipulated the orthographic quality of specific target words by, for example, displaying them in faint versus bold font. The predictions were as follows: If the familiarity check corresponds to an early, orthographic stage of lexical processing, then this manipulation should affect the time required to complete the familiarity check on the target word [i.e., $t(L_1)$], and hence the duration of the fixation on that word. Because lexical access involves the full activation of semantic codes, however, this manipulation should not affect the time required to complete lexical access [i.e., $t(L_2)$] or affect the parafoveal processing of the post-target word (see Fig. 2). These predictions were confirmed: Although reducing the font quality of the target words increased the fixation durations on those words, this manipulation did not reduce the parafoveal processing of the post-target words (as would have been evident by increased fixation durations on those words).

The second experiment was specifically intended to examine the time course over which two lexical variables, frequency of occurrence and case alteration (e.g., *account* vs. *AcCoUnT*), influence readers' "decisions" about when to move their eyes (Reingold, Yang, & Rayner, 2010). In this experiment, subjects read sentences containing high- and low-frequency targets words that were displayed either in normal or alternating case. The key findings were that both manipulations affected standard first-pass measures (e.g., gaze durations), but that only word frequency affected the duration of the first of multiple fixations. Because the first of multiple fixations presumably reflected instances where lexical processing of a word was incomplete (thus requiring one or more additional fixations), the observed pattern of results was interpreted as being consistent with the hypothesis that lexical processing is completed in two successive stages: an initial stage that is influenced by word frequency, and a subsequent stage that is influenced by both word frequency and case alternation. This interpretation is therefore consistent with the E-Z Reader model's basic assumption that lexical processing is completed in two successive stages.

The third experiment that was specifically designed to evaluate the familiarity-check assumption used *event-related potentials* (*ERP*s) to examine the predicted time course of the familiarity check (Reichle, Tokowicz, Liu, & Perfetti, 2011). During each trial of this experiment, subjects viewed two simultaneously displayed letter strings, with one string always being presented in the center of the computer monitor and the other being displayed randomly either 14° to the left or right of center. The subjects' task was to indicate as quickly and accurately as possible (via button presses) whether either of the letter strings corresponded to a non-word. On the majority of the trials, both letter strings were words, and subjects did whatever amount of processing was necessary to "know" that the center letter string was a word and then quickly moved their eyes to the peripheral letter string to do the same. The frequency of the centrally displayed word was also manipulated, with the two primary questions being: (1) Would this manipulation be reflected in the ERP components related to lexical processing? (2) Would these components be predictive of when subjects' eye moved?

To answer these questions, the ERP data were first aligned to the onset of the saccade to the peripheral letter string so that ERP components related to word processing could be identified prior to the eye movement, and to determine whether these components occurred at times that are predicted by the E-Z Reader model. (Because of the durations of the saccadic programming stages, the familiarity check is predicted to occur on average 125 ms prior to saccade onsets.) Consistent with the model's assumptions, ERP components were identified during an interval spanning the predicted familiarity check time and were modulated by word frequency. These frequency-modulated components were strongly predictive of saccade onset and were weaker in magnitude when the ERP data were aligned to the beginning of the trial (rather than the onset of the saccade), indicating that an early stage of lexical processing occurs rapidly enough to allow sufficient time for the initiation and completion of saccadic programming and is aligned with the execution of the saccade (which, on average, occurred 289 ms after stimulus onset). The results thus provide an important proof of concept that the relative timing of the familiarity check and saccadic programming are plausible using physiological methods.

Interim Conclusions

The preceding review indicates that there is enough theoretical and empirical support for the notion of a familiarity check to take the hypothesis seriously. As it has been discussed so far, however, this evidence is limited in two important respects. First, if the familiarity check does play an important role in determining when the eyes move during reading, the evidence is completely silent about whether the same mechanism plays an important role in other, non-reading tasks. As indicted previously, our simulations of non-reading tasks suggest that the familiarity check is not always operative, and that its functional utility may be less in tasks like visual search. The second limitation is directly related to the first: Although we have made many claims (e.g., see Reichle et al., 2012) that the familiarity check has functional utility in reading, so far we have not actually provided evidence supporting this claim. In other words, while it is certainly plausible that using a word's familiarity as a heuristic for deciding when to move the eyes off of the word, and while it certainly sounds plausible that this heuristic permits efficient reading, neither of these assertions has been demonstrated. In the sections that follow, we address this limitation using simulations to support both of these assertions. By doing this, we strengthen the support for the familiarity-check assumption and—perhaps more importantly—provide some new insights into why the familiarity check is not universally employed in the service of performing all visual-cognitive tasks.

Simulations

General Method

Unless otherwise noted, the simulations that are reported below were completed using the model, materials, and parameter values described by Reichle et al. (2012), and 1,000 statistical subjects per condition. In contrast to the prior simulations, which specifically examined both when and where the eyes moved in a variety of tasks, the simulations reported below only examine one global dependent measure of task efficiency—the overall rate of word/stimulus processing as measured using words/stimuli per minute. All of the reported simulations are also similar in that the main variable of interest is the parameter Δ (see Equation 3) and the role that it plays in modulating overall task efficiency in reading and non-reading tasks.

Simulation 1

The first simulation was intended to examine how parametric manipulations of the value of Δ affected the overall reading rate. To do this, the overall mean maximal time to process words [i.e., $t(L_1) + t(L_2)$] was set at one of six different values: 50, 100, 150, 200, 250, and 300 ms. Note that these values do not include the 50 ms necessary to complete the pre-attentive stage of visual processing nor the slowing effect of limited visual acuity (see Equation 2). These six processing times were intended to span what might be considered the range of plausible times to process words during reading (and possibly other stimuli in reading-like tasks). For each of these six conditions, the proportion of the total time that was necessary to complete the familiarity check [i.e., $t(L_1)$] versus lexical access [i.e., $t(L_2)$] was then varied by manipulating the values of two parameters (α_1 and Δ) so that $t(L_1)$ was either 100%, 75%, 50%, or 25% of the total word-processing time. (For the sake of simplicity, the values of the other parameters that modulate the rate of lexical processing as a function of a word's frequency and predictability were simply set equal to constant values across the simulations; i.e., $\alpha_2 = 2$ and $\alpha_3 = 30$.) The simulation as described was then repeated twice: first with post-lexical processing enabled and then again with post-lexical processing disabled. The latter was done to examine the consequences of a stage of processing that would presumably be unnecessary in some non-reading tasks (e.g., scene viewing). The simulation results are shown in Figure 3, with Panels A and B respectively showing the reading rates with post-lexical processing disabled and enabled.

As Panels A and B of Figure 3 show, the parameter manipulations resulted in three pronounced results. First, increasing the mean maximal time to process words markedly slowed the overall reading rate, reducing it from $M = 833$ wpm when $t(L_1) + t(L_2) = 50$ ms down to $M = 227$ wpm when $t(L_1) + t(L_2) = 300$ ms. This result is expected for the obvious reason that slowing lexical processing slows the rate at which the eyes move from one word to the next, thereby slowing the reading rate[3].

The second result is that post-lexical processing also modestly slowed the overall reading rate, reducing it from $M = 466$ wpm when integration was disabled down to $M = 387$ wpm when it was enabled. Although this result is also expected, it confirms earlier claims that integration "can lag behind ongoing lexical processing, often generating no discernable effects on the progression of the eyes through the text," but that integration difficulty will "occasionally manifest very rapidly in the form of pauses and/or regressions" (Reichle et al., 2009, p. 16). The default values of the integration parameters that were used in this simulation only resulted in occasional integration failure, thus slowing the reading rate only modestly.

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[3] The average reading rate for college-level readers is 250–350 words per minute (Rayner & Pollatsek, 1989).

Finally, the last, and most important, result is that reducing the time required to complete the familiarity check also markedly increased the overall reading rate, increasing it from M = 323 wpm when the familiarity check consumed 100% of the total word-processing time to M = 586 wpm when it consumed only 25% of the time. Although this is an obvious consequence of making the familiarity check more rapid, what is by no means obvious is that the facilitation was evident across all conditions, irrespective of the absolute mean maximal time to process words and irrespective of whether post-lexical processing was enabled. This result is a direct consequence of the fact that, in the E-Z Reader model, limited visual acuity only affects the familiarity check (see Equation 2) and not the completion of lexical access. This effectively means that there is no penalty for moving the eyes from a word too soon because whatever processing of the word must be completed after the trigger to move the eyes from the word has occurred (i.e., the completion of L_1) will by assumption only entail the activation of lexical codes (i.e., corresponding to L_2) that are impervious to limitations in visual acuity. As already discussed, this distinction between an early stage of lexical processing in which the rate of processing is affected by the quality of the visual input versus a later stage that is not affected by stimulus quality is consistent with the results of Reingold and Rayner’s (2006) experiment (see also Reingold et al., 2010).

The finding that the introduction of a familiarity check always enhanced the overall reading rate therefore suggests that the familiarity check is beneficial over a wide range of reading abilities. It is also seemingly contrary to the intuition that the familiarity check can be initiated too soon—that the “triggering” of a saccade can occur too soon, causing the eyes to leave a word prematurely and thereby slowing the overall rate of reading. More will be said about this possibly counter-intuitive result in the General Discussion.

Simulation 2

Given the finding in Simulation 1 that the familiarity check always facilitated reading performance, the second simulation was intended to examine this possibility in the context of a non-reading task, target-word search (Rayner & Fischer, 1996). In this task, subjects are instructed to scan through text and locate all occurrences of a specific target word (e.g., *zebra*). The main findings from this task are that fixations are much shorter in duration than in reading and that the effects of word frequency are largely absent.

In simulating this task using the E-Z Reader model, Reichle et al. (2012) found that the parameter values that provided the best fit of the data were ones in which the value of Δ was set equal to zero. This was interpreted as evidence that the task is performed without the use of a familiarity check; that in scanning for specific target words, a single signal simultaneously triggers both the movement of the eyes and attention from one word to the next. One explanation for why this would occur is that the subjects only need some minimal amount of visual information to discriminate the target word from non-targets, and that the time that is required to access this information cannot benefit from using word familiarity.

To examine this hypothesis further, the second simulation reported here used the materials and parameter values from Reichle et al.’s (2012) second simulation of Rayner and Fischer’s (1996) target-word search task. As in Simulation 1, the total time to process the words [i.e., $t(L_1) + t(L_2)$] was held constant, but the values of two parameters (α_1 and Δ) were manipulated so that $t(L_1)$ was either 100%, 75%, 50%, or 25% of the total word-processing time. The overall search rates are shown in Panel C of Figure 3. (The target-word search rates are shown along with the reading rates from the previous simulation to facilitate direct between-task comparisons.)

As Figure 3C shows, reducing the time necessary to complete the familiarity check increased the overall search rate, increasing it from M = 659 wpm when the familiarity check consumed 100% of the total word-processing time to *M* = 1098 wpm when it consumed only 25% of the time. Thus, consistent with what was suggested in Simulation 1, the inclusion of a familiarity check speeds task performance even when the task is already being completed at a very rapid rate (*M* = 839 wpm for search vs. *M* = 427 wpm for reading). Again, this result is not unexpected given the model's assumption that visual acuity only affects $t(L_1)$. However, the result does raise the question of why such facilitation would not be expected to occur in the actual target-word search task (Rayner & Fischer, 1996). In other words, what is to prevent subjects who are searching for target words from adopting increasingly more liberal "threshold" for initiating saccadic programming, thereby reducing individual fixation durations to whatever minimal time is necessary to complete visual encoding and then program saccades?

One possible reason has to do with the simple fact that one can already search for a target word more rapidly than one can read (Rayner & Fischer, 1996). This suggests that, in the search task, it is not necessary to complete the identification of each word prior to initiating a saccadic program in order to move their eyes to the next word. It is likely that the word-search task can instead be performed using partial information about the words (e.g., their length, initial letters, shape, etc.) to help discriminate targets from non-targets because this information is more rapidly available than the semantic codes that are necessary for reading. Despite the fact that this partial word information is rapidly available, however, there is still a limit on how rapidly it is available for use. Furthermore, it may not be possible to use any type of information—including that provided by familiarity—more rapidly than as determined by this limit. If this explanation is correct, then the "trigger" to move the eyes and attention when searching for a target word may simply correspond to the minimal time that is required to convert the visual features into whatever information is being used to decide that the word being fixated is not the target. As such, it might not be possible to improve performance in this task by using familiarity because performance is already at ceiling because the "non-target" decision is so easy.

Simulation 3

Simulation 2 examined the effect of word familiarity in a non-reading task that can be performed very rapidly—target-word search. Simulation 3 was intended to determine if the introduction of a familiarity check might facilitate performance of a non-reading task that, by virtue of the task, can only be performed very slowly—searching for the letter *O* in a linear array of Landolt *C*s (Williams & Pollatsek, 2007). (A Landolt *C* is essentially a circle with a small segment missing; both the size and location of the missing segment can be manipulated to make it more or less difficult to discriminate for an *O*.) The letters are arranged into clusters (or "words") of four letters each, with the clusters separated by a space that is one character wide. Moreover, the size of the gap for the *C*s was held constant within a cluster but varied between clusters so that the relationship between the difficulty of processing a "word" and eye movement measures could be assessed. The key findings from this paradigm were that fixations were much longer in duration than those in reading and that the fixation duration on a cluster of four letters was modulated by Landolt-*C* gap size. There was also a notable absence of a spillover effect, suggesting that a single signal was used to initiate saccadic programming and to shift attention. That is, because relative differences in the difficulty of identifying Landolt-*C* clusters did not affect the looking times on subsequent clusters, a single signal (e.g., full identification of the fixated cluster) probably triggered both saccadic programming and the shifting of attention in this task, contrary to what is posited to occur during reading according to the E-Z Reader model (see Fig. 2).

In simulating this task using E-Z Reader, Reichle et al. (2012) manipulated the value of the parameter that controls the effect of visual acuity, ε, to modulate the rate of Landolt-*C* processing as a function of their gap size. The logic of the assumption is based on the fact that, because Landolt *C*'s are relative homogeneous stimuli, there is very little "lexical" processing to be completed; instead, the primary determinant of the time required to discriminate a Landolt *C* from an *O* is the relative ease of seeing the gap in the former, and hence how the perception of gap size is modulated by visual acuity. Based on this logic and the absence of spillover effects in this task (Williams & Pollatsek, 2007), the value of Δ was also set equal to zero. By assumption, then, the task was performed without the use of a familiarity check, but rather a single stage corresponding to stimulus identification.

To examine this hypothesis further, the third simulation reported here used the materials and parameter values from Reichle et al.'s (2012) simulation of Williams and Pollatsek's (2007) Landolt-*C* search task. As in Simulations 1 and 2, the total time to process the stimuli [i.e., $t(L_1) + t(L_2)$] was held constant, but the values of two parameters (α_1 and Δ) were manipulated so that $t(L_1)$ was 100%, 75%, 50%, or 25% of the total stimulus-processing time. The specific parameter values and the overall search rates are shown in Figure 4. The increasing values of the ε parameter correspond to decreasing (and thus more difficult to see) gap sizes.

As Figure 4 shows, the results of Simulation 3 are consistent with the previous two simulations in that the introduction of a familiarity check facilitated task performance, increasing the overall search rate from $M = 83$ clusters per minute (*cpm*) when the familiarity check consumed 100% of the total word-processing time to $M = 153$ cpm when it consumed 25% of the time. This speed up occurred despite the fact that the overall rate was much slower than in reading ($M = 114$ cpm for search vs. $M = 427$ wpm for reading) and despite that fact that limited visual acuity slowed stimulus processing to a much greater degree than in either reading or target-word search. Again, this is not unexpected given the model's assumption that visual acuity only affects $t(L_1)$. However, as with the prior simulation of the target-word search, this result also raises the question of why such facilitation from having a separate signal from a familiarity check to initiate a saccadic program apparently did not facilitate the actual Landolt-*C* search task (Williams & Pollatsek, 2007). In other words, what is to prevent subjects who are performing the task from adopting a more liberal criterion (e.g., stimulus familiarity rather than identification) for initiating saccadic programming?

One possible reason is that, in performing the Landolt-*C* search task, it is necessary to process each Landolt *C* well enough to be discriminated from the letter *0*. As such, the task seems to demand the full identification of each letter in the stimulus cluster, rather than either some amount of partial information (as was posited in target-word search) or familiarity (as is posited in reading). Put differently, what may distinguish the Landolt-*C* search task from reading is that there may be no partial activation that would be a reliable index of whether the cluster of four letters contains an *O*. One possibility of such an index is that there is some computation of total (or average) "gapness" in the cluster. However, if the cluster contained three *C*s with large gaps and an *O*, this gapness computation may very well induce the viewer to move prematurely to the next cluster and miss the target.

Perhaps there is some other global computation that can be a reliable index of whether a target is present in a cluster before actually examining each letter, but it might be difficult for subjects to figure out what it is. Related to this is the fact that the Landolt-*C* stimuli are both novel and homogeneous; the novelty of the stimuli would make it impossible for subjects to use pre-established stimulus representations (e.g., of individual clusters) to discriminate *C*s from *O*s, and the homogeneity of the stimuli would be problematic for a discrimination based on any type of signal-detection theory because the stimuli would presumably share a very high degree of (un)familiarity. This explanation is consistent with the finding that repeated exposure to non-target tokens in the context of the Landolt-*C* search task results in an analog to the word frequency effect: Non-targets that are encountered more often tend to be the recipients of shorter fixations, suggesting that subjects are forming representations of repeated non-targets and that some aspect of those non-targets (e.g., their familiarity) is in turn influencing the “decisions” about how long to look at the stimuli (Vanyukov, Warren, Wheeler, & Reichle, 2012).

General Discussion

To summarize, the simulations that are reported in this article indicate that the introduction of a familiarity-check mechanism consistently facilitated the rate of task performance, irrespective of whether the task was reading, target-word search, or searching for an *O* among Landolt *C*'s, and irrespective of the absolute time that was needed to process the words or stimuli. As indicated, this finding is seemingly at odds with the basic intuition that, to be useful, the familiarity check must not initiate saccadic programming too late or early. Although there are reasons why this is not likely to be true in the two non-reading tasks that were discussed, the results of the first simulation are problematic in that they seem to suggest that there is never a cost—at least not in terms of the overall reading rate—for initiating saccadic programming too soon. Is this conclusion correct? And if not, then what other factors might curtail the overly liberal use of a familiarity-check mechanism for deciding when to move the eyes during reading?

First, it is unlikely that this conclusion is correct, and that, in the context of reading, the familiarity check may slow the overall rate of reading if it is initiated too soon. The ERP experiment (Reichle et al., 2011) that was discussed earlier indicated that the ERP components that were modulated by word frequency and that were interpreted as corresponding to the familiarity check were evident within a specific time window, and not earlier or later. This provides some empirical evidence that the familiarity check actually takes some amount of time to be completed, and that it probably does not simply correspond to some minimal processing deadline that always initiates saccadic programming as rapidly as possible.

There are two obvious ways in which the familiarity check could hinder reading, especially if it is set too early. First, something may happen in the second, L_2, stage that indicates that there is unexpected difficulty (e.g., that the duration of the L_2 stage may not always be a fixed multiple of the duration of the L_1 stage, as specified in Equation 3). As a result, the eyes may move on to word n+1 before processing of word n is complete. Although the current version of the model posits that L_2 processing is not affected by visual acuity and hence the location of the fixation, this may be a bit of an oversimplification, especially if the eyes are fixated on a different word than the one attended. Second, it is possible that a word will be misidentified, and that a too rapid movement of the eyes increases the probability that such a misidentification will occur. Again, if this is the case, then the familiarity check could have negative effects on reading and reading rate. Factors such as these are currently outside of the E-Z Reader model's theoretical scope, but are paradoxically suggested by the results reported in this article.

Let us consider the second factor, as the evidence for it is clearer (Slattery, 2009; Levy, Bicknell, Slattery, & Rayner, 2009). As indicated above, as the model is currently implemented, there is no cost associated with moving the eyes from word n to n+1 before the former has been completely identified. This is because: (a) the second stage of lexical processing of word n continues for 50 ms (i.e., the duration of the eye-to-mind lag) after the saccade using whatever visual information was extracted from the fixation on word n, and (b) even after processing resumes from the new viewing location (i.e., on word n+1), both the rate and accuracy of processing are assumed to be unaffected. This is unlikely to be true of human readers, however, because a poorer viewing location is likely to increase the chances of misidentifying word *n*. This would be especially true if the fixation location is not on the word that is attended as there could easily be "crosstalk" between the letters of the fixated and attended words. This hypothesis is consistent with the patterns of eye movements that are observed with elderly readers, who, because of having slower rates of lexical processing, tend to both skip more words and make more regressions (Rayner et al., 2006). By this interpretation, the increased skipping rates cause more words to be parafoveally processed, from the right of the skipped words, which in turn causes more of those words to be misidentified. Thus, another factor that might cause people to be more conservative in their use of word familiarity is the fact that its too liberal use is likely to result in many misidentifications, possibility causing further disruption (e.g., problems with post-lexical processing) and thereby limiting the overall reading rate.

To test the feasibility of this word mis-identification hypothesis, we completed a simulation that was identical to the first except that it included an additional assumption that rapid familiarity checks [i.e., $t(L_1) < 50$ ms] on word *n* caused the probability of integration failure on that word to increase from 0.01 (i.e., the default value of p_F) to 0.5. Simulation 4 thus provides a way to determine what happens in the model if the familiarity check completes too rapidly, thereby increasing the likelihood of mis-identifying a word and causing problems with integration[4]. As Figure 5 shows, assuming that $\Delta > 0$ in two cases [i.e., when $t(L_1) + t(L_2) = 100$ ms, going from $\Delta = 0.33$ to $\Delta = 1$, and when $t(L_1) + t(L_2) = 200$ ms, going from $\Delta = 1$ to $\Delta = 3$] caused the efficiency gain associated with the familiarity check to actually become a cost. The fact that the relative gains versus costs were irregular across the conditions reflects the fact that what was considered to be "too fast" for the familiarity check (i.e., 50 ms) was both arbitrary and a threshold that worked in an all-or-none manner with certain durations of $t(L_1)$. One might hope to generate a more graded effect of word-misidentification by introducing a more realistic (but also more complicated) assumption that the probability of mis-identification gradually increases as $t(L_1)$ decreases.

There are also probably a number of other specific task constraints that prevent the more liberal use of the familiarity check. In reading, for example, strict serial allocation of attention automatically delimits the rate of lexical processing, and hence any advantage that might result from rapidly moving the eyes. In other words, irrespective of whether or not there is any cost associated with moving the eyes too far ahead of attention, it doesn't convey any advantage because each word still has to be identified in its correct order in the text (Pollatsek & Rayner, 1999; Reichle, Liversedge, Pollatesek, & Rayner, 2009; Rayner, Pollatsek, Liversedge, & Reichle, 2009). In a similar vein, the assumption that lexical and post-lexical processing are loosely coupled so that the latter doesn't lag too far behind the former would also work against any benefit that might come from moving the eyes too soon. For example, in E-Z Reader, any benefit that might come from moving the eyes from word *n* to *n*+1 in the service of identifying word *n*+1 more rapidly could also increase the likelihood of word *n*+1 being identified before word *n* had been integrated, thereby resulting in integration failure and an inter-word regression back to word *n*.

Finally, another possibility is that the moment-to-moment "decisions" about when to move the eyes off of a word or stimulus reflects the dynamic interaction between some indicator of processing fluency (e.g., familiarity) that tend to trigger the initiation of saccadic programming, and one or more indicators of processing difficulty that tend to inhibit or prolong saccadic programming. Such an interactive mechanism was recently proposed to

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[4] The simulations reported by Pollatsek, Juhasz, Reichle, Machacek, and Rayner (2008) provide a similar test of this word mis-identification hypothesis.

explain the rapidly discernable effects of word frequency during reading and as part of a more general taxonomy of mechanisms that are known to influence saccadic programming and hence fixation durations during reading (Reingold, Reichle, Glaholt, & Sheridan, 2012). As related to the current discussion, such an interactive mechanism might allow for a fairly liberal use of familiarity because, once initiated, saccadic programming could then be prolonged if processing difficulty was subsequently encountered. Of course, the viability of such an interactive mechanism has not been formally evaluated (e.g., by being implemented in the framework of a computational model of eye-movement control), and as such this explanation remains tentative.

In closing, it is important to emphasize that the task demands of reading are tightly constrained and well enough understood that hypotheses such as the ones that were just articulated are fairly easy to generate and—at least in principle—test. Although many might argue that the task demands of other visual-cognitive tasks are equally well constrained and/or understood, the types of hypotheses that can be developed to explain how word familiarity affects reading efficiency are simply not possible without formal models that can be used to explain both *when* and *where* the eyes move in these non-reading tasks. This special issue suggests that the endeavor to develop such models is being taken seriously, and that such models will be used in the suggested capacity in the very near future. Such models will undoubtedly provide important points of theoretical contrast to our model and the work that we have done to examine the common basis for eye-movement control in reading versus other visual-cognitive tasks. We are therefore optimistic that the next decade will prove to be as productive in advancing our understand of eye-movement control in these other tasks as the past decade has been in advancing our understanding of eye-movement control in reading.

Acknowledgments

The work reported in this article was supported by grants HD053639 and HD26765 from the National Institutes of Health.

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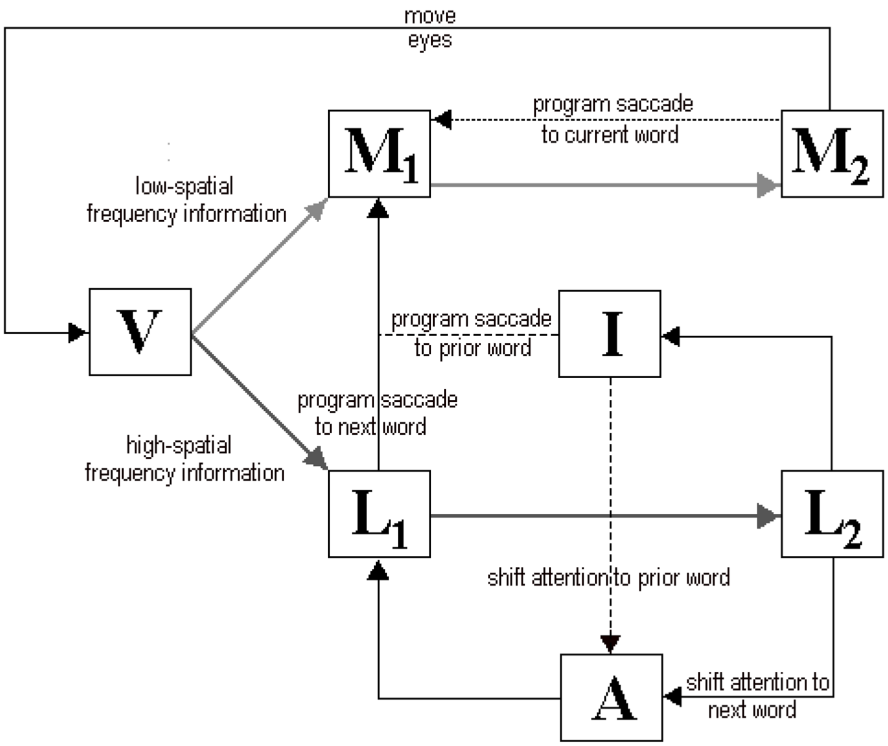

Figure 1.

A schematic diagram of the E-Z Reader model of eye-movement control during reading. The labeled components are as follows: (1) *V* = pre-attentive visual processing; (2) L_1 = familiarity check; (3) L_2 = completion of lexical access; (4) *A* = attention; (5) *I* = post-lexical integration; (6) M_1 = labile stage of saccadic programming; and (7) M_2 = non-labile stage of saccadic programming.

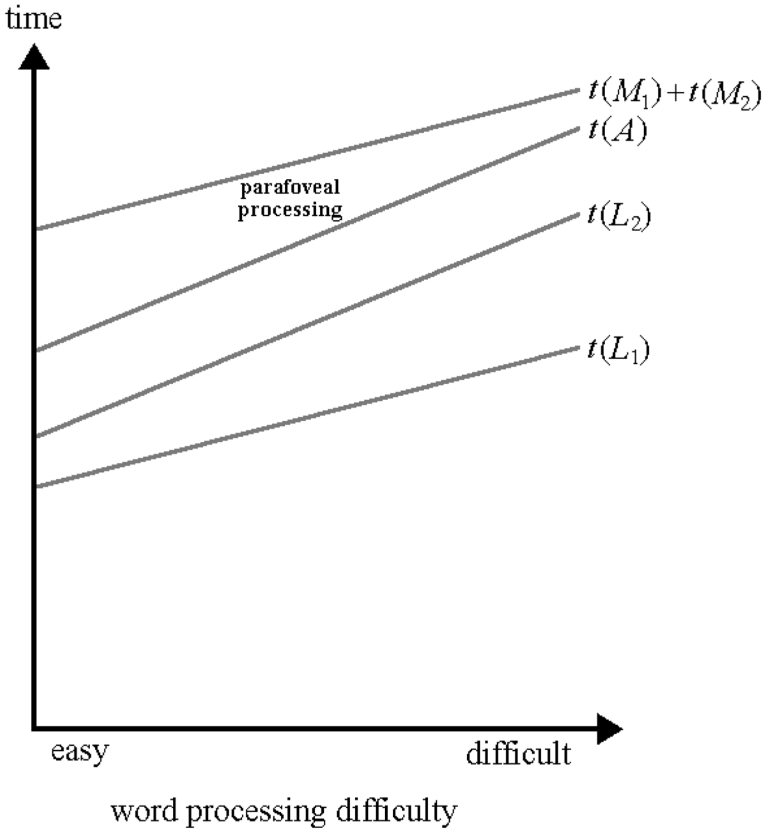

Figure 2.

A schematic diagram showing how the time to complete the familiarity check, $t(L_1)$, relates to the time require to complete lexical access, $t(L_2)$, shift attention, $t(A)$, and complete saccadic programming, $t(M_1) + t(M_2)$, all as a function of word-processing difficulty. As the figure indicates, the amount of time that is available for parafoveal processing of word n+1 (i.e., the time between when attention shifts to word n+1 and when the eyes actually move to word n+1) varies as a function of the processing difficulty of word n.

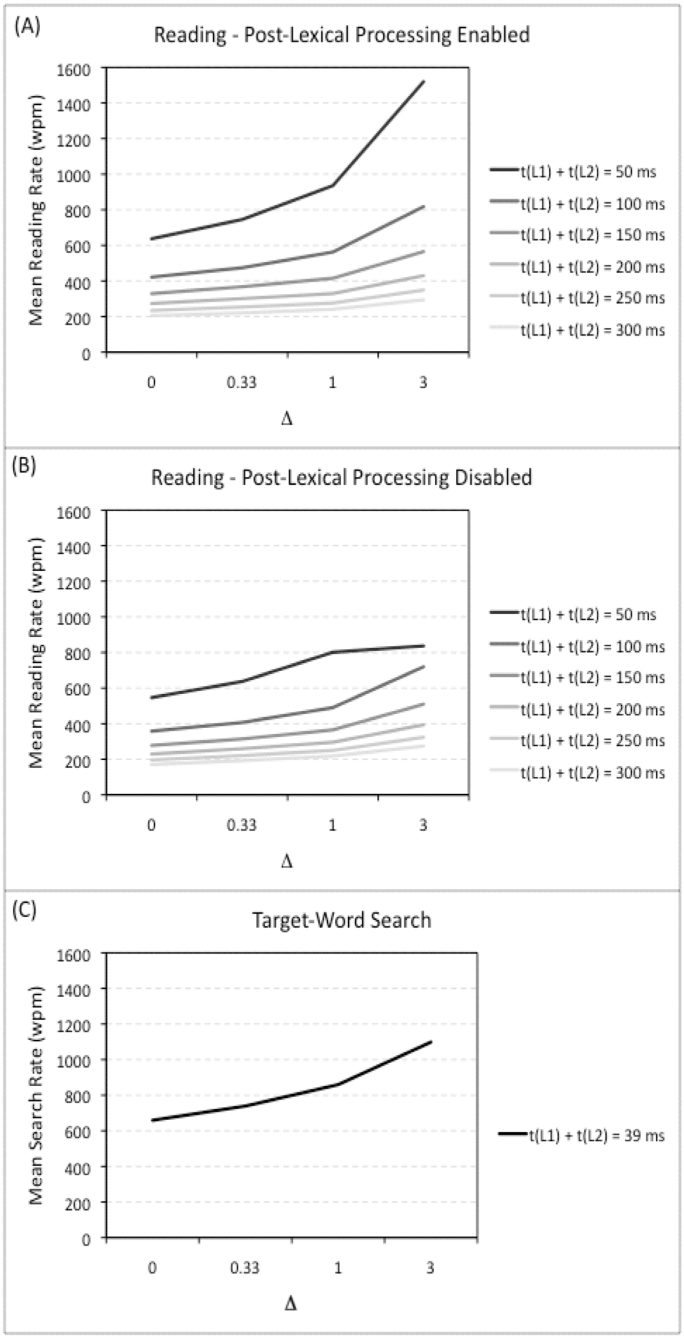

Figure 3.

Panel A: Results of Simulation 1, which examined how the absolute and relative times to complete L_1 and L_2 affected reading rate (in words per minute, *wpm*) with post-lexical processing disabled. Panel B: Results of Simulation 1, which examined how the absolute and relative times to complete L_1 and L_2 affected reading rate (in words per minute, *wpm*) with post-lexical processing enabled. Panel C: Results of Simulation 2, which examined how the absolute and relative times to complete L_1 and L_2 affected target-word search rate (in words per minute, *wpm*). Note that task performance is shown on a common scale to facilitate between-task comparisons.

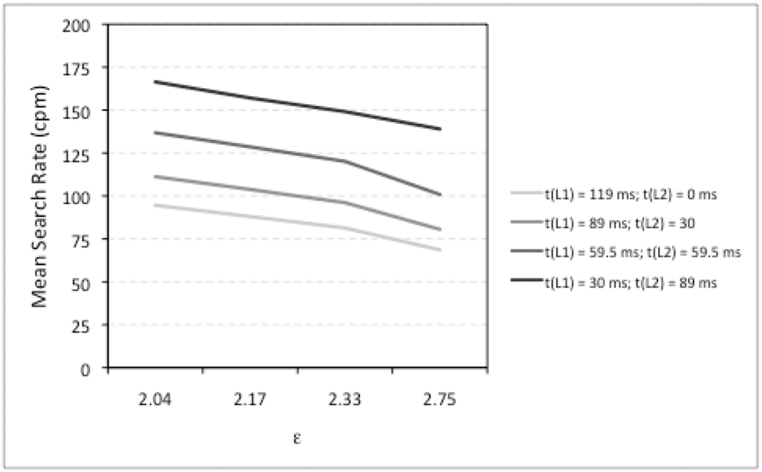

Figure 4.

Results of Simulation 3, which examined how the absolute and relative times to complete L_1 and L_2 affected Landolt-*C* search rate (in clusters per minute, *cpm*).

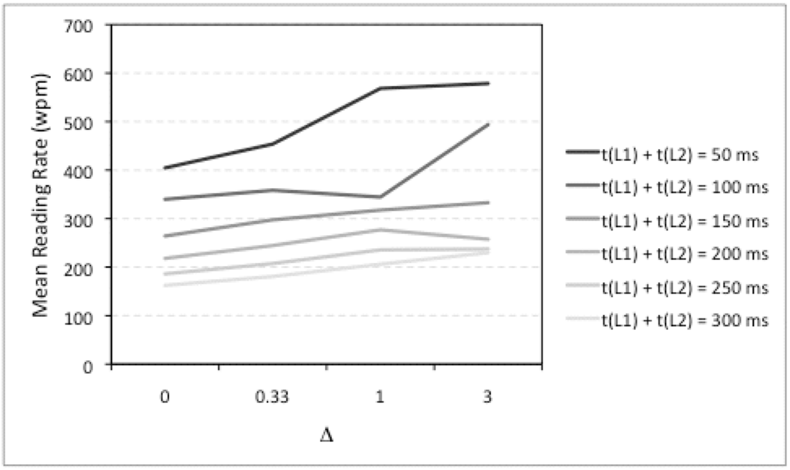

Figure 5.

Results of Simulation 4, which examined how the absolute and relative times to complete L_1 and L_2 affected reading rate (in words per minute, *wpm*) with rapid familiarity checks [i.e., $t(L_1) < 50$ ms] increasing the likelihood ($p = 0.5$) of word mis-identification and integration difficulty.

Table 1

E-Z Reader parameter interpretations and default values.

Type of Processing	Parameter	Interpretation	Values
Word Identification	α_1	mean maximum L_1 time (ms)	104
	α_2	effect of frequency on L_1 time (ms)	3.5
	α_3	effect of predictability on L_1 time (ms)	39
	Δ	proportional difference between L_1 and L_2	0.34
	A	mean attention-shift time (ms)	25
Higher-Level Language Processing	I	mean integration time (ms)	25
	p_F	probability of integration failure	0.05
	p_N	probability of regression being directed to prior word	0.5
Saccadic Programming & Execution	M_1	mean labile programming time (ms)	125
	ξ	proportion of M_1 allocated to “preparatory” sub-stage	0.5
	$M_{1,R}$	additional time required for labile regressive programs (ms)	30
	M_2	mean non-labile programming time (ms)	25
	Ψ	optimal saccade length (character spaces)	7
	Ω_1	effect of launch-site fixation duration of systematic error	6.0
	Ω_2	effect of launch-site fixation duration of systematic error	3
	η_1	mean maximum random error (character spaces)	0.5
	η_2	effect of saccade length on random error (character spaces)	0.15
	λ	increase in refixation probability (character spaces)	0.16
	S	saccade duration (ms)	25
Visual Processing	V	eye-to-brain transmission time (ms)	50
	ε	effect of visual acuity	1.15
General	$\sigma\gamma$	standard deviation of gamma distributions	0.22