Psychophysiology, 48 (2011), 993–1003. Wiley Periodicals, Inc. Printed in the USA.

DOI: 10.1111/j.1469-8986.2011.01169.x

Testing an assumption of the E-Z Reader model of eye-movement control during reading: Using event-related potentials to examine the familiarity check

ERIK D. REICHLE,[a] NATASHA TOKOWICZ,[a] YING LIU,[b] AND CHARLES A. PERFETTI[a]

[a]Department of Psychology and Learning Research and Development Center, University of Pittsburgh, Pittsburgh, Pennsylvania, USA
[b]School of Education, Liaoning Normal University, Dalian, China

Abstract

According to the E-Z Reader model of eye-movement control, the completion of an early stage of lexical processing, the familiarity check, causes the eyes to move forward during reading (Reichle, Pollatsek, Fisher, & Rayner, 1998). Here, we report an event-related potential (ERP) experiment designed to examine the hypothesized familiarity check at the electrophysiological level. The results indicate ERP components modulated by word frequency at the time of the predicted familiarity check. These findings are consistent with the hypothesis that an early stage of lexical processing is linked to the "decisions" about when to move the eyes during reading.

One of the fundamental assumptions of *serial-attention-shift models* of eye-movement control in reading (Just & Carpenter, 1987; Reichle, Pollatsek, Fisher, & Rayner, 1998; Salvucci, 2001; for a review of these models, see Reichle, 2010) is that the completion of some stage of lexical processing of word *n* provides a signal to the oculomotor system to begin programming a saccade to move the eyes to word $n+1$. The two challenges faced by such models are to specify exactly what the hypothesized cognitive process actually corresponds to (e.g., accessing a word's meaning vs. some preliminary stage of lexical processing), and to demonstrate that, in the context of normal reading, this process can be completed rapidly enough to trigger saccadic programming. This constraint on the timing of the cognitive process arises from the apparent paradox that, whereas both lexical processing (Rayner & Pollatsek, 1989) and saccadic programming (Becker & Jürgens, 1979; Leff, Scott, Rothwell, & Wise, 2001; McPeek, Skavenski, & Nakayama, 2000; Molker & Fischer, 1999; Rayner, Slowiaczek, Clifton, & Bertera, 1983; Vergilino & Beauvillain, 2000) are known to be relatively slow, the individual fixations during reading tend to be fairly short in duration (Kliegl, Nuthmann, & Engbert, 2006; Schilling, Rayner, & Chumbley, 1998). Given this quandary, it is not immediately obvious how something as sluggish as lexical processing can be the "engine" that drives the eye forward during reading. It is therefore important to examine the basic assumption of serial-attention-shift models more closely, to determine both *if* and—if so—*what* cognitive process or processes might be responsible for determining when the eyes move during reading.

The present experiment was designed to identify the electrophysiological correlates of lexical processing that occur *prior* to eye movements and that predict *when* the eyes move from one word to another. In the experiment, participants made lexical decisions about pairs of simultaneously presented but spatially separated letter strings so that we could examine the neural correlates of lexical processing that preceded the eye movements from one word to the other. Our specific hypothesis was that we should observe event-related potential (ERP) components that are modulated by word frequency and whose timing prior to saccade onsets allows enough time for them to serve as a signal to begin saccadic programming. Before we describe the specific details of our experiment, however, we will first provide some background about one specific serial-attention-shift model that motivated this work: the *E-Z Reader* model of eye-movement control during reading (Pollatsek, Reichle, & Rayner, 2006; Rayner, Ashby, Pollatsek, & Reichle, 2004; Rayner, Li, & Pollatsek, 2007; Reichle, 2010; Reichle et al., 1998; Reichle, Rayner, & Pollatsek, 2003; Reichle, Warren, & McConnell, 2009).

The E-Z Reader model was developed to account for the patterns of eye movements that are observed when people are reading text. The two core assumptions of the model are that (1)

Portions of this work were presented at the 2006 Annual Meeting for the Society for the Scientific Study of Reading, Vancouver, Canada. This work was supported by the Department of Education, Institute of Education Sciences Grant R305G020006 that was awarded to the first and last authors. Natasha Tokowicz was supported by NSF-BCS 0745372 during the writing of this article. We thank the research assistants in the University of Pittsburgh Reading and Language Labs—especially Eddie Wlotko and Susan Dunlap—for their assistance in collecting the data. Finally, we thank Ralf Engbert, Peter Gianaros, Reinhold Kliegl, Simon Liversedge, Keith Rayner, and an anonymous reviewer for their helpful suggestions for improving earlier versions of this article.

Address correspondence to: Erik Reichle, University of Pittsburgh, 635 LRDC, 3939 O'Hara St., Pittsburgh, PA 15260. E-mail: reichle@pitt.edu

the type of attention that is necessary to support lexical processing is allocated serially, to only one word at a time, and (2) that the completion of an early stage of lexical processing (called the *familiarity check* or L_1) initiates the programming of a saccade to move the eyes to the next word. The first assumption is motivated by (a) an extensive literature suggesting that attention can only be allocated to one visual ''object'' (which, in the context of reading, corresponds to an individual word) so that the features of that object can be ''bound'' into a unitary representation (e.g., Reichle, Vanyukov, Laurent, & Warren, 2008; Treisman & Gelade, 1980) and (b) the fact that word order conveys important linguistic information that is maintained via the serial processing of words (Pollatsek & Rayner, 1999; see also Rayner, Pollatsek, Liversedge, & Reichle, 2009; Reichle, Liversedge, Pollatsek, & Rayner, 2009). The second assumption (that the familiarity check triggers eye movements) was motivated less by a priori consideration of empirical and theoretical work and was instead adopted as a way to explain the severe timing constraint that was mentioned earlier. The experiment reported in this article thus represents one attempt to evaluate this assumption, using electrophysiological methods to examine the specific time course and nature of the hypothesized familiarity check. In other words, the experiment provides new information about what is happening in the brain during an interval of time that—according to the E-Z Reader model—should correspond to the familiarity check.

Figure 1 is a schematic diagram of the model (Pollatsek et al., 2006), including both the functional components of the model (represented by labeled boxes) and the cortical and subcortical structures to which these components are (tentatively) thought to correspond (Reichle et al., 2003).[1] As the figure shows, the model is a formal description of how the systems involved in vision, attention, lexical processing, and oculomotor control interact to produce the moment-to-moment ''decisions'' about when and where a reader's eyes will move. Although the specific assumptions of the model have been instantiated at a fairly abstract, functional level (as described below), Heinzle, Hepp, and Martin (2010) have recently developed a ''biologically realistic'' spiking-neuron model of eye-movement control in reading that shares the two core assumptions of E-Z Reader: that attention is allocated in a serial manner and that an early stage of word identification provides the signal to initiate saccadic programming. Thus, the experiment reported in this article also provides a direct test of one of the core assumptions of Heinzle et al.'s model.

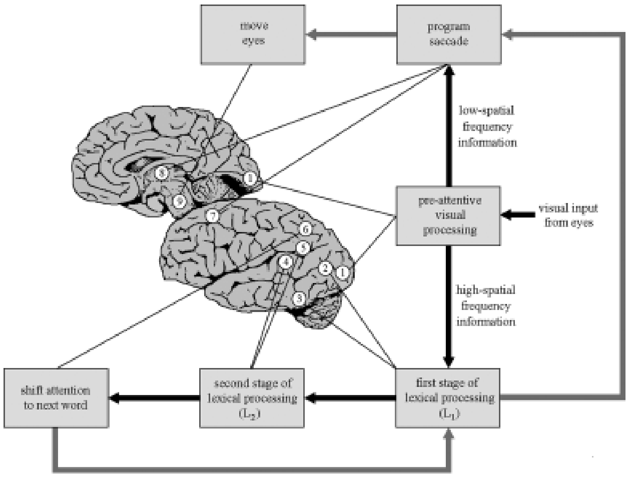

Figure 1. Schematic diagram of the E-Z Reader model of eye-movement control during reading and of the tentative mapping between the model's components and the cortical and subcortical brain structures involved in reading. The figure of the brain shows the lateral view of the left hemisphere in front of a medial view of the right hemisphere, with the following regions indicated by numbers: (1) primary visual cortex (Brodmann's Area [BA] 17), (2) extrastriate cortex (BAs 18 and 19), (3) left inferior temporal gyrus (i.e., fusiform gyrus; BAs 20 and 37), (4) left posterior middle and temporal gyri (i.e., Wernicke's area; BAs 21 and 22), (5) left posterior inferior parietal lobule (i.e., angular gyrus; BA 39), (6) intraparietal sulci (i.e., parietal eye fields; BAs 7 and 40), (7) left superior prefrontal and posterior superior frontal gyri (i.e., frontal eye fields; BAs 6 and 8), (8) pulvinar nuclei of thalamus, and (9) the superior colloculi and motor circuits of the brain stem that control the extraocular muscles that move the eyes. Although the right-hemisphere homologues of regions 6 and 7 are not shown in the diagram, they are also part of the functional networks that are responsible for shifting attention and programming saccades.

As Figure 1 shows, according to the E-Z Reader model, visual information on the printed page is propagated from the retina to the primary visual cortex, with both the low- and high-spatial-frequency information being propagated in parallel across the visual field. After 50 ms (i.e., the duration of the *eye-to-brain lag*; Clark, Fan, & Hillyard, 1995; Foxe & Simpson, 2002; Mouchetant-Rostaing, Gaird, Bentin, Aguera, & Pernier, 2000; Van Rullen & Thorpe, 2001), the low-spatial-frequency information is used for identifying word boundaries and locating saccade targets while some small portion of the high-spatial-frequency information is selectively attended for lexical processing. This lexical processing culminates in the activation of a word's meaning, which in the model is represented by the box labeled L_2. The completion of this stage causes attention to shift to the next word, so that it can be processed. Because an earlier stage of lexical processing (labeled L_1) is the trigger to begin programming a saccade to the next word, the shifting of attention is dissociated from the programming of saccades; in other words, the completion of L_1 causes the oculomotor system to begin programming an eye movement to the next word, whereas the subsequent completion of L_2 causes attention (and thus lexical processing) to shift to the next word. Attention shifts are thus decoupled from saccadic programming according to the model. Finally, the remaining assumptions of the model are all related to the actual programming of saccades. First, saccades are programmed in two stages: a labile stage that is subject to cancellation by the initiation of subsequent saccades, followed by a nonlabile stage that is not subject to cancellation. Second, all saccades are directed toward the centers of words, but are subject to both random and systematic motor error that causes the fixation landing-site distributions to be approximately normal in

---

[1] Our experiment was originally motivated by E-Z Reader 9 (Pollatsek et al., 2006). Although a subsequent version of the model has recently been developed (i.e., E-Z Reader 10; Reichle, Warren, et al., 2009), it largely differs from its predecessor in that it includes additional assumptions about how difficulty with higher level (i.e., postlexical) language processing interrupts lexical processing and the forward progression of the eyes, resulting in pauses, regressions, or both. Because our experiment used the lexical decision task and hence involved no higher level language processing and because the core assumption about the relationship between lexical processing and eye movements is the same across all versions of E-Z Reader, we have opted to limit our discussion to the earlier but conceptually simpler E-Z Reader 9. Although our task does not involve natural reading, the core assumptions of E-Z Reader are sufficient to make predictions about our task if one assumes that the familiarity check triggers the saccadic programming that is necessary to move participants' eyes from the centrally displayed words.

shape, with a tendency for short/long saccades to over/under shoot their intended targets (Rayner, 1979). The final assumption is that, on average, saccades take 125 ms to program and 25 ms to execute (Rayner et al., 1983). All three of these assumptions about saccadic programming were based on the seminal work of Becker and Jürgens (1979) and others (e.g., McConkie, Kerr, Reddix, & Zola, 1988), and allow the model to account for a variety of findings related to eye-movement control (e.g., the characteristics of the landing-site distributions that were just mentioned).

To understand the logic of the current experiment, it is important to understand how the times required to complete L_1 and L_2 are determined. The mean time that is required to complete L_1 on a given word, $t(L_1)$, is a function of that word's frequency of occurrence in printed text (as tabulated by Francis & Kucera, 1982),[2] its within-sentence predictability (as determined through cloze-task norms), and the mean disparity between each of its letters and the character position that is being fixated. In Equation 1, α_1 (= 122 ms), α_2 (= 4 ms), and α_3 (= 10 ms) are free parameters whose values were chosen to maximize how well the model accounts for the patterns of fixation durations and probabilities that were observed in the corpus of sentences used by Schilling et al. (1998) to examine the effects of word frequency. Likewise, ε (= 1.15) is a free parameter that modulates the degree to which visual acuity slows the rate of lexical processing (via increasing how much time is required to complete lexical processing) as a function of the mean distance (measured in character spaces) between each of the i letters of the word that is being processed and the fixation point, with N being the number of letters in the word being processed.

$$t(L_1) = [\alpha_1 - \alpha_2 \ln(\mathit{frequency}) - \alpha_3\, \mathit{predictability}]\varepsilon^{\sum_i |\mathit{letter}_i - \mathit{fixation}|/N}. \tag{1}$$

Equation 1 thus allows the model to predict that—with all else being equal—frequent words, predictable words, and short words will be the recipients of fewer and shorter fixations than less frequent, less predictable, and/or longer words. In addition, words that are further from the center of fixation will be processed less rapidly (from the parafovea) than words that are closer to the center of fixation because of the assumption of limited visual acuity (i.e., as specified by the right-most term in Equation 1). All of these aspects of the model's behavior are in accordance with empirical results (for a review, see Rayner, 1998). Finally, during each Monte Carlo simulation run of the model, the actual time that is required to complete L_1 for a given word is a random deviate that is sampled from a gamma distribution having a mean defined by $t(L_1)$ and a standard deviation equal to .22 of $t(L_1)$.

The mean time that is required to complete L_2, $t(L_2)$, is given by Equation 2, where $\Delta(= .5)$ is a free parameter that makes $t(L_2)$ a fixed proportion of $t(L_1)$. Because the amount of time that is required to program a saccade is a constant (= 125 ms), the model predicts that—with all else being equal—there will be less parafoveal processing of word $n+1$ from word n (i.e., attention will shift from word n to word $n+1$ later, closer in time to when the eyes actually move to word $n+1$) when word n is difficult to process. This assumption allows the model to predict the interaction between the processing difficulty of word n and the amount of preview benefit that is observed on word $n+1$ (Henderson & Ferreira, 1990), as well as the *spillover effect*, or the finding that the fixations on words that follow difficult-to-process words are often inflated relative to fixations that follow easier-to-process words (Kliegl et al., 2006; Rayner & Duffy, 1986).

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

As already mentioned, L_1 corresponds to a preliminary stage of lexical processing that indicates that it is "safe" to start programming a saccade to the next word. By this, we simply mean that, if a saccade is initiated to move the eyes from word n to word $n+1$ upon the completion of L_1 for word n, then the saccade will (on average) not move the eyes too soon, before word n has been identified, nor too late, so that a substantial amount of time is not wasted processing word $n+1$ from word n. The timing of saccade initiation is critical because both of the aforementioned situations would slow the overall rate of reading; both situations would result in a substantial amount of lexical processing being done from the parafovea, where visual acuity is poor and lexical processing is both slow and prone to error (Rayner & Morrison, 1981). The familiarity check can thus be viewed as being a "cheat" or heuristic that allows the reader to move his or her eyes efficiently, so as to maximize the overall reading rate while maintaining some minimal level of comprehension. Given this conceptualization, what else can be said about this surmised process?

As it has been described thus far, the familiarity check corresponds to some early stage of lexical processing that indicates that access to a word's meaning is imminent. As such, the familiarity check is assumed to be more rapid than lexical access. Alternative conceptualizations of the process have included the idea that it is based on a rapidly available "familiarity" response, perhaps based on a recognition signal that might precede the slower retrieval of a word's meaning (Atkinson & Juola, 1973; Yonelinas, 2002). Alternatively, the familiarity check could correspond to one or more specific types of lexical information, such as abstract orthographic and/or phonological codes that may become available before a word's semantic codes. Of course, these two hypotheses are not mutually exclusive, and one might imagine that readers, when faced with the task of learning how to move their eyes efficiently, might, over the course of many years, learn contingencies among many types of information (e.g., word length, global familiarity, etc.) that are predictive of when a word's meaning is likely to become available. These learned contingencies might then allow the reader's oculomotor system to become tuned in a manner that would afford efficient eye-movement control. One example of how this might occur was provided by Reichle and Laurent (2006); their simulations using artificial reading agents demonstrated that such contingencies could, in fact, be learned, resulting in the emergence of a process that closely resembled the familiarity check posited in the E-Z Reader model.

The aforementioned hypotheses share the common assumption that some early aspect of lexical processing is correlated with—and therefore predictive of—*when* a saccade will move the eyes from one word to another. By either interpretation, therefore, the familiarity check should be completed early enough during lexical processing to allow sufficient time for the subsequent completion of saccadic programming. In addition, the speed of the familiarity check should be modulated by lexical variables (e.g., word frequency). In the present experiment, ERPs were used as an index of lexical processing to determine what relevant processing occurs in the cerebral cortex prior to the onset

---

[2] In principle, any word frequency corpus could be used to compute the amount of time required to complete lexical processing in the E-Z Reader model.

of a saccade from one word to another. As will be shown below, the results of our analyses indicated ERP components that were modulated by word frequency during a time interval that, according to the E-Z Reader model, should include the familiarity check. This suggests that lexical processing may be initiated rapidly enough to allow sufficient time for saccadic programming, in accordance with E-Z Reader. We shall return to these issues in the General Discussion.

Finally, before we describe the details of our experiment, we will first provide an overview of the basic logic of our experimental design. Past attempts to examine lexical processing and eye movements using ERPs have taken one of two general approaches. The first has been to run parallel ERP and eye-tracking experiments, that is, collecting both ERP and eye-movement data from a single group of participants performing a single task on the same materials at two different times (Sereno, Rayner, & Posner, 1998). Although this approach has been extremely informative, it was adopted largely because of the inherent difficulties associated with the simultaneous recording of eye movements and ERPs (e.g., the electrical activity associated with eye movements obscures ERPs). Recent attempts to overcome these technical challenges have been successful, allowing true simultaneous recording of both eye-movement and ERP data (Baccino & Manunta, 2005). Although this second approach has also been informative, it relies on algorithms to remove artifacts in the ERP data that are caused by the eye movements themselves (Coles & Rugg, 1995) and thus may be subject to a different set of limitations and criticisms. The present experiment is unique in that it employs neither of these two approaches, but instead uses only ERPs to measure cortical activity and eye movements simultaneously. Thus, our basic approach is to have participants make lexical decisions to simultaneously presented but spatially separated pairs of letter strings, and then (1) use the electrical signals recorded at the *electrooculographic* (*EOG*) electrodes to identify the onsets of saccades from words (e.g., Young & Sheena, 1975), (2) align and average the ERP data from the other electrodes to these saccade *onsets*, and (3) then examine the ERP components that occurred *prior* to the saccades and that are modulated by word frequency. This approach is similar to an ERP response-locking approach (e.g., the error-related negativity; Gehring, Goss, Coles, Meyer, & Donchin, 1993) and allows us to answer the question of what cognitive process or processes determine when the eyes move.

Method

Participants

The participants were 16 right-handed native English speakers from the University of Pittsburgh who received credit toward a research participation requirement.[3] The main conditions of interest (e.g., those involving word frequency) contained no fewer than 25 observations.

Stimuli

The stimuli were 200 English words (50 high- and 50 low-frequency critical words and 100 filler words) and 40 pseudo-words generated by changing one letter from a real English word. The critical stimuli were always presented at fixation, and the filler stimuli were always presented in the periphery. High-frequency words had a mean frequency of 221.8 occurrences per million (*SD* = 125.75; Francis & Kucera, 1982) and a mean length of 4.48 letters (*SD* = 0.93). Low-frequency words had a mean frequency of 9.54 (*SD* = 3.38) and a mean length of 4.54 letters (*SD* = 1.01). Filler words had a mean frequency of 69.74 (*SD* = 71.46) and a mean length of 4.52 letters (*SD* = 0.98). Pseudo-words had a mean length of 4.48 letters (*SD* = 1.01). The stimuli included more words than pseudo-words at fixation because we were not interested in the lexical *decision* per se, but were instead interested in the ERP components related to lexical processing that preceded eye movements from the centrally displayed letter strings when those letter strings were words. Because of the task design, there is no requirement for the participants to respond while viewing the centrally displayed letter strings, even if they are real words, but the task design encourages the participants to attend to the stimuli to perform the task.

The filler stimuli were divided into two lists matched for word length and, with words, frequency. These lists were used to counterbalance stimulus presentation so that each item was displayed in both the left and right locations across two versions of the experiment; each participant viewed only one version of the experiment and saw each word only once. Participants completed a total of 120 trials, 80 of which (66.7%) had a correct "yes" response.

Procedure

Participants performed a speeded lexical decision task on pairs of stimuli (see Figure 2A). Participants initiated each trial by pressing a space bar while a fixation cross was displayed in the center of the computer screen. One letter string (word or pseudo-word) was then displayed in the center of the screen while another letter string was simultaneously displayed in one of two possible viewing locations: approximately − 14° or + 14° from center. Viewing order was randomized using E-Prime (Psychological Software Tools, Pittsburgh, PA). Participants pressed a key marked "Y" with their left hand if both letter strings were words and pressed a key marked "N" with their right hand if either string was a pseudo-word. Feedback about response time and

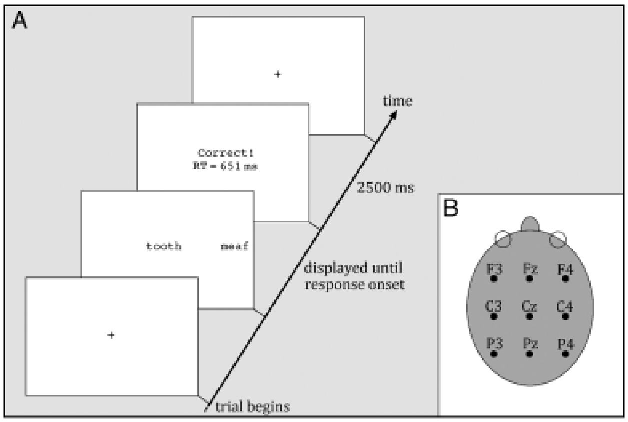

Figure 2. Procedure used for individual experimental trials (A) and the nine electrodes used in the ERP analyses (B). Participants initiated each trial by pressing the spacebar. Two letter strings then appeared until a response was initiated, ending the trial with feedback about the response and then beginning the next trial.

---

[3] The data from 9 additional participants were not included in our analyses because of problems with the equipment, failure to comply with instructions, or because they provided fewer than 10 usable trials in one or more conditions.

accuracy was then displayed for 2500 ms. Participants completed six practice trials before completing 120 experimental trials and were instructed to perform the task as quickly and accurately as possible. Because of these instructions and because the letter strings were randomly displayed an equal number of times across trials in both viewing locations, the optimal way to perform the task is to continue looking at the central fixation cross until the two letter strings appear, do whatever processing is necessary to make the lexical decision about the central letter string, and then (if that letter string is a word) rapidly move the eyes to the peripheral letter string to facilitate its processing. Participants likely performed the task in this manner because the central letter string was a word on 83.3% of the trials (making an eye movement to the peripheral letter string necessary) and because the large visual angle also made it necessary to look at the peripheral letter strings to determine if it was a word or not. Data analyses are thus limited to those trials involving centrally displayed words followed by saccades to peripherally displayed letter strings. (We therefore discarded those trials on which the centrally displayed letter string was a pseudo-word.)

ERP Recording and Preprocessing

The data were recorded using 128-channel Electrical Geodesics Sensor Nets and associated amplifiers and NetStation acquisition software (Electrical Geodesics, Inc., Eugene, OR). The electrodes used in the analyses of mean amplitude correspond to these international 10-20 system (Jasper, 1958) locations: F3, Fz, F4, C3, Cz, C4, P3, Pz, and P4 (see Figure 2B). These electrodes were selected to maximize comparability with previous studies. Impedance was kept below 40 kΩ, as recommended for use with EGI equipment (Ferree, Luu, Russell, & Tucker, 2001). Cz was used as the reference electrode during recording; data were re-referenced off-line to the average of the left and right mastoids. This reference was more appropriate than an average reference because the eye movements broadly disrupted activity recorded across the front and center of the scalp (in a manner that was not entirely symmetrical and therefore not canceled out by averaging), thereby violating the assumptions of average reference, but the recordings at the mastoid electrodes were relatively unaffected by eye movements. The sampling rate was 1000 Hz, and the hardware filter setting was between 0.1 and 400 Hz. The data were filtered off-line using a 30-Hz low-pass filter. Eye movements and blinks were monitored using two horizontal and four vertical eye channels. When possible, data from bad channels were replaced with data from the surrounding electrodes using standardized interpolation algorithms (NetStation 2.0). The 100 ms prior to the stimulus onset was used as the baseline for each trial.

Results

Behavioral Responses

Table 1 shows the mean response latencies (in milliseconds, for correct responses) and response accuracies (proportion correct) for trials involving centrally displayed words. The standard errors of these means are also shown, in parentheses. The data were subjected to inferential statistical analyses of variance (ANOVAs), using the correct *response* (“yes” vs. “no”), the *frequency* of the centrally displayed word (high vs. low) and the saccade *direction* (left vs. right) as within-participant factors. (With the response latencies, missing data from one cell for one participant were replaced by the mean of that cell across participants.) Finally, although we report all reliable interactions, we interpret only those that are central to our hypotheses.

Table 1. *Mean Response Latencies (in Milliseconds; for Correct Trials) Accuracies (Proportion Correct), and Standard Errors of Means (in Parentheses) for Trials Involving Centrally Displayed Words, as a function of Response, Frequency of the Centrally Displayed Word, and Saccade Direction*

	Latencies				Accuracies			
	Yes		No		Yes		No	
	Left	Right	Left	Right	Left	Right	Left	Right
High-frequency	925	916	1051	1113	.98	.98	.94	.8
words	(48.6)	(51.1)	(60)	(53.9)	(.01)	(.01)	(.04)	(.07)
Low-frequency	972	947	1092	1189	.98	.98	.79	.76
words	(53.8)	(46)	(56)	(60.4)	(.01)	(.01)	(.05)	(.06)

The analysis of the response latencies indicated that participants were faster making “yes” than “no” responses (940 vs. 1,111 ms, respectively), $F_1(1,15) = 121.9$, $MS_e = 7,714$, $p < .001$, were faster responding to high-frequency than low-frequency words (1,002 vs. 1,050 ms, respectively), $F_1(1,15) = 6.23$, $MS_e = 12,157$, $p < .05$, and were marginally faster responding following leftward than rightward saccades (1,010 vs. 1,041 ms, respectively), $F_1(1,15) = 3.14$, $MS_e = 10,135$, $p = .097$. There was also a reliable Response × Direction interaction, $F_1(1,15) = 18.01$, $MS_e = 4,132$, $p < .01$, with faster “yes” responses following rightward (932 ms) than leftward (949 ms) saccades, but faster “no” responses following leftward (1,072 ms) than rightward (1,151 ms) saccades.

The analysis of response accuracies mirrored those of the latencies: Participants were more accurate making “yes” than “no” responses (.98 vs. .82, respectively), $F_1(1,15) = 18.85$, $MS_e = .042$, $p < .01$, and showed trends toward being more accurate with high- than low-frequency words (.93 vs. .88, respectively), $F_1(1,15) = 4.35$, $MS_e = .017$, $p = .054$, and following leftward than rightward saccades (.92 vs. .88, respectively), $F_1(1,15) = 3.71$, $MS_e = .014$, $p = .073$. These results were qualified by several marginal interactions, however, including Response × Frequency, $F_1(1,15) = 3.75$, $MS_e = .018$, $p = .072$, Response × Direction, $F_1(1,15) = 3.63$, $MS_e = .015$, $p = .076$, Frequency × Direction, $F_1(1,15) = 4.42$, $MS_e = .0057$, $p = .053$, and Response × Frequency × Direction, $F_1(1,15) = 3.14$, $MS_e = .0081$, $p = .097$. Although none of these observed interactions involving saccade direction were expected, they are not central to the hypotheses being tested. The more important findings are those involving response and word frequency, both of which were expected because “yes” responses are often faster and/or more accurate than “no” responses (e.g., Kroll & Merves, 1986) and because high-frequency words are generally identified more rapidly, accurately, or both than low-frequency words (Balota & Chumbley, 1984; Schilling et al., 1998).

Item analyses were also conducted on response latencies and accuracies using word *frequency* (high vs. low) as a between-items factor and saccade direction (left vs. right) as a within-item factor. The ANOVA of response latencies showed a trend of faster responses to high- than low-frequency words (962 vs. 1,012 ms, respectively), $F_2(1,78) = 3.25$, $MS_e = 30396.93$, $p = .075$. Neither the main effect of saccade direction nor its interaction with word frequency were significant (both Fs < 1.5, both ps $> .27$).

The ANOVA of response accuracies showed a tendency for more accurate responses for trials involving leftward than rightward saccades (.96 vs. .93, respectively), $F_2(1,78) = 2.92$, $MS_e = .009$, $p = .092$, but no effect of frequency or Frequency × Direction interaction (both Fs < 1, both ps $> .38$).

Eye Movements

Because the eyes are dipoles having positive and negative polarity, eye movements cause large deflections in the ERP signal, and consequently trials containing saccades are most often discarded (Coles & Rugg, 1995). In the present experiment, we exploited the fact that saccades cause large deflections in the electroencephalogram record and used an algorithm developed by Csibra, Johnson, and Tucker (1997; Csibra, Tucker, & Johnson, 1998; see also Joyce, Gorodnitsky, King, & Kutas, 2002) to determine when our participants moved their eyes. To do this, we first subtracted the *electrooculographic* (*EOG*) output recorded from the outer canthus of one eye from that of the other and then located differences of 1 μV or more extending across 20 consecutive milliseconds. The beginnings of these intervals correspond to the saccade onset times. (Although the magnitude and sign of the difference can be used to determine saccade length and direction, respectively, it was not necessary to use this information because participants had to move their eyes to the peripherally displayed letter strings to perform the task.)

Table 2 shows the mean saccade latencies (in milliseconds) and standard errors of these means (in parentheses) for trials on which the center letter strings were real words. The mean saccade latencies were analyzed using an ANOVA with fixation word *frequency* (high vs. low) and saccade *direction* (left vs. right) as within-participant factors. As predicted, the main effect of word frequency was reliable, $F(1,15) = 26.28$, $MS_e = 482.60$, $p < .001$; participants moved their eyes more rapidly from centrally displayed high-frequency words (275 ms after stimulus onset) than low-frequency words (303 ms). This result suggests that whatever lexical processing had to be completed to determine that the letter strings were not pseudo-words was done more rapidly for high- than low-frequency words. This explanation is consistent with previous results showing significant correlations between the response times to perform tasks that require participants to identify high- and low-frequency target words (e.g., lexical decision) and the fixation durations on those same words during natural reading; high-frequency words are identified more rapidly and are fixated for shorter periods of time than are low-frequency words (Schilling et al., 1998).

Although saccadic direction was not predicted to have an effect, it was marginal, $F(1,15) = 3.83$, $MS_e = 1{,}291$, $p = .069$, with faster eye movements to letter strings on the left (280 ms) than the right (298 ms). More important, however, is the fact that saccade direction did not interact with word frequency ($F < 1$). Although saccadic direction is not an intrinsically interesting theoretical variable, it is included in the analyses reported next because of its potential relationship to related studies in the literature at the request of an anonymous reviewer.

Table 2. *Mean Observed Saccade Onset Latencies (in Milliseconds, with Standard Errors of Means in Parentheses), as a Function of Saccade Direction and Frequency of the Centrally Displayed Word*

	Left	Right
High-frequency words	266 (20.7)	283 (13.1)
Low-frequency words	294 (22.4)	312 (17.1)

Finally, it is worth noting that the observed variability associated with the saccades is in close agreement to the hypothesized variability that is assumed to be associated with the various lexical and oculomotor processes in the E-Z Reader model. Across the four conditions in Table 2, the standard deviations associated with the saccade-onset latencies are, on average, 25.5% of the mean latencies, which is numerically close to what is assumed in E-Z Reader: that process durations have standard deviations equal to 22% of their mean durations.

ERP Data

Analyses were performed on the data collected from the nine electrodes (see Figure 2B). The grand-average waveforms for the left and right EOG electrodes and for the nine electrodes used in our analyses are shown in Figure 3. The first set of analyses used the procedures developed by Sereno et al. (1998) to examine the time course of lexical processing in an ERP experiment involving high- and low-frequency words having either consistent or inconsistent spelling-to-sound correspondences. These first analyses follow standard stimulus-locked conventions in that the ERP waveforms were averaged from the beginning of the trial (i.e., stimulus onset) to allow direct comparisons between our results and those reported in the literature (e.g., Sereno et al., 1998). The second set of analyses involved aligning the ERP data not forward from stimulus onset, but rather backward from saccade onset, to more precisely examine the ERP components that precede the eye movements from the centrally to peripherally displayed letter strings; thus, these are a form of response-locked component. These components were then compared to the saccade-onset and lexical-processing times predicted (see Figure 4) by the E-Z Reader model of eye-movement control (Pollatsek et al., 2006; Reichle, Pollatsek, & Rayner, 2006).

In the first set of analyses (following Sereno et al., 1998), mean amplitudes for each of the nine electrodes were calculated across three consecutive 32-ms time intervals: (1) 100–132 ms after stimulus onset, (2) 132–164 ms after stimulus onset, and (3) 164–196 ms after stimulus onset. Visual inspection verified that the use of these time windows would not effectively cancel the effects because of polarity shifts. The mean amplitudes for each interval were then analyzed with separate ANOVAs for each interval. These ANOVAs used word *frequency* (high vs. low), "*hemisphere*" (left = F3, C3, P3 vs. midline = Fz, Cz, Pz vs. right = F4, C4, P4), "*lobe*" (frontal = F3, Fz, F4 vs. central = C3, Cz, C4 vs. parietal = P3, Pz, P4), and saccade *direction* (left vs. right) as within-participant factors. The Huynh–Feldt adjustment was used where appropriate to correct for violations of sphericity.[4] Following convention, we do not report main effects of or interactions between electrode site factors that do not include manipulated factors.

The ANOVA indicated that, in the first and second intervals (100–132 ms and 132–164 ms after stimulus onset), there were only marginal main effects of word frequency, $F(1,15) = 3.23$, $MS_e = 11.69$, $p = .093$, and $F(1,15) = 3.07$, $MS_e = 16.92$, $p = .1$, respectively. In the first interval, the mean ERP amplitudes for high- and low-frequency words were .11 μV and .62 μV, respectively; the values for high- and low-frequency words in the second

---

[4] Psychophysiological data often violate the analysis of variance assumption of sphericity (see Jennings, 1987; Picton et al., 2000).

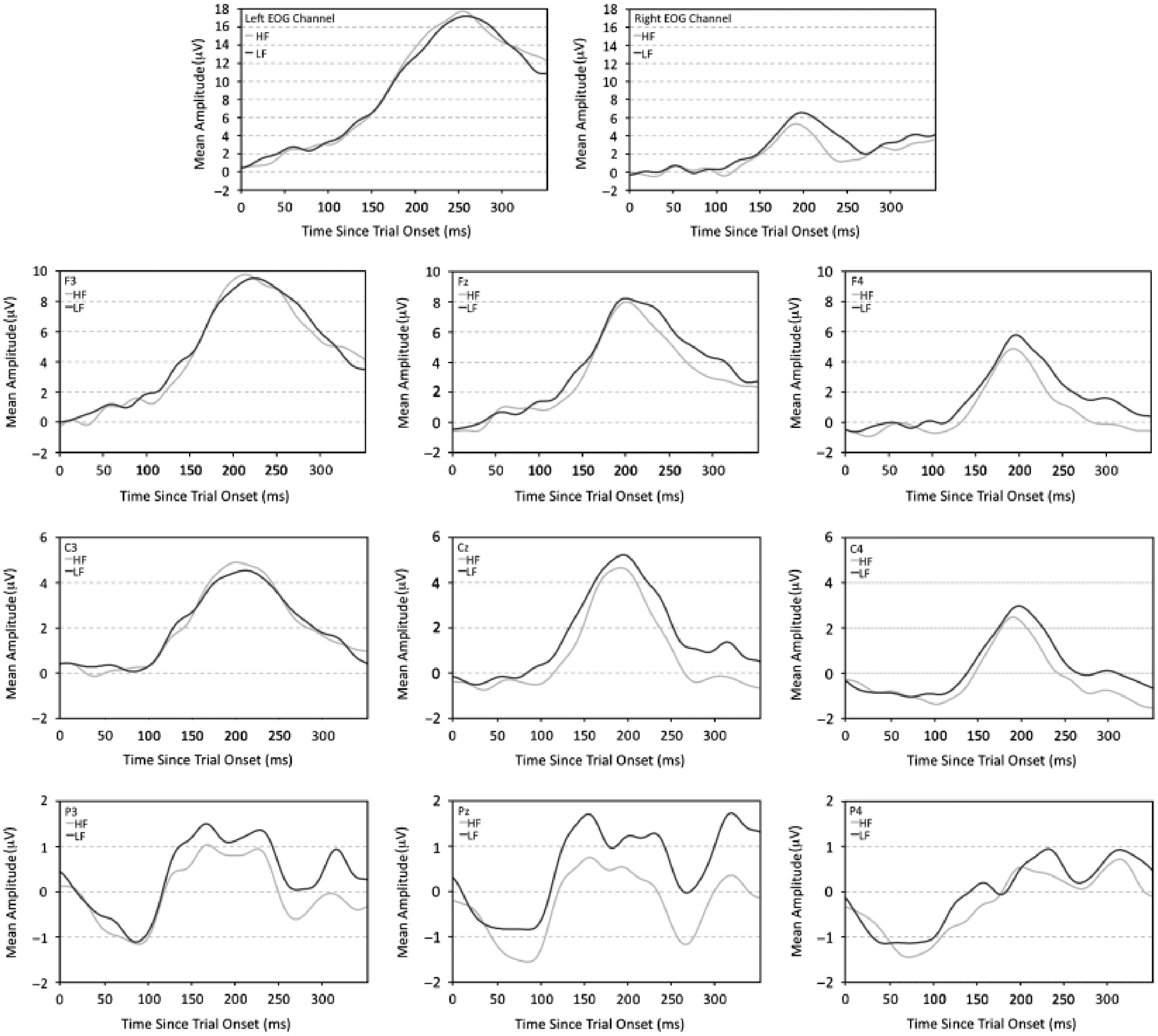

Figure 3. Grand-average waveforms for high- (HF) and low-frequency (LF) words from the left and right electrooculographic (EOG) channels and the nine channels used in our analyses (see Figure 2B).

interval were 1.59 μV and 2.19 μV, respectively. These results are consistent with previous reports showing that early ERP components tend to be less positive for high-frequency words (Dambacher, Kliegl, Hoffmann, & Jacobs, 2006; Hauk & Pulvermüller, 2004; Polich & Donchin, 1988; Sereno et al., 1998; Sereno, Brewer, & O'Donnell, 2003). In the third interval (164–196 ms), only the Frequency × Hemisphere × Lobe interaction was reliable, $F(4,60) = 2.66$, $MS_e = .68$, $p < .05$. This interaction demonstrates lexical processing that is differentially recorded across the surface of the scalp. None of the other interactions involving word frequency were statistically reliable in any of the time intervals (all $F\text{s} < 2.1$). Finally, none of the main effects of saccade direction or interactions involving saccade direction and frequency were reliable (all $F\text{s} < 1.2$).

As already mentioned, our second set of analyses was completed to examine the time course of lexical processing relative to both the observed saccade-onset times and those predicted by the E-Z Reader model of eye-movement control (Pollatsek et al., 2006; Reichle et al., 2006). The model was used to generate predictions both about when the familiarity check is expected to have occurred for the centrally displayed words in the two conditions, and when the eyes should have moved from these words to the peripherally displayed letter strings.[5] Figure 4 shows both

---

[5] The predicted times required to complete the familiarity checks for the centrally displayed high- and low-frequency words were obtained by adding the duration of the eye-to-brain lag (= 50 ms) to the values obtained from Equation 1 using frequencies of 221.8 and 9.54 for the high- and low-frequency words, respectively. (The duration of the eye-to-brain lag can be ignored in simulations of normal reading because lexical processing following a saccade is assumed to continue using the information that was acquired during the previous fixation; this was not possible in generating predictions for our experiment because the words only appeared at the beginning of the trial.) Because the words were completely unpredictable in the context our experiment, predictability was set equal

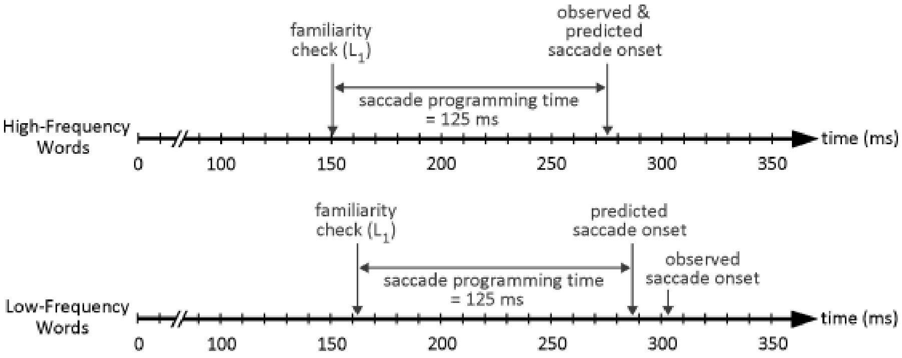

Figure 4. Observed saccade onset times for high- and low-frequency words and the E-Z Reader model's predicted saccade-onset and familiarity-check times.

the predicted and observed saccade-onset times. Note that the model accurately predicts when the eyes should move. That is, for the high-frequency words, the mean predicted saccade-onset time was exactly the same as the observed time (275 ms after stimulus onset). Similarly, for the low-frequency words, a two-tailed contrast indicated that the mean predicted and observed saccade-onset times were not statistically different from each other (288 vs. 303 ms, respectively; $t < 1$). The small differences between the observed and predicted saccade-onset times are probably due to both participant and task differences (e.g., the model's parameter values were selected to fit the eye-tracking data from Schilling et al., 1998).

The second set of analyses was based on the starting assumption that trial (stimulus) onset may not be the most appropriate time from which to align the ERP waveforms (Hoffman, Simons, & Houck, 1983)—especially if one wants to examine the cognitive processes that precede or predict when the eyes move—and that a better benchmark for aligning and comparing ERP waveforms might instead be the saccade-onset times. The grand-average saccade-aligned waveforms for the high- and low-frequency words are shown in Figure 5. In contrast to our first set of analyses, in which the waveforms were aligned from trial onset, the current analyses provide an alternative method to examine the waveforms that are generated by significant cognitive events (e.g., lexical processing of high- vs. low-frequency words) more directly by aligning waveforms to events (e.g., saccades) that may be more closely tied to cognitive processing than are the trial onsets. A similar approach has been used to examine *eye-fixation related potentials* (*EFRPs*), where the ERP waveforms were aligned to *fixation* onset to more closely examine the cognitive events that occurred *after* eye movements (Baccino & Manunta, 2005; Kazai & Yagi, 1999); the current approach differs from these approaches in that we are aligning the waveforms to *saccade* onsets to more closely examine the cognitive events that occur *before* eye movements.

The ERP data were aligned to the observed saccade-onset times and three 32-ms time windows were defined, with the second (middle) window being centered on the mean predicted familiarity-check times for the high- and low-frequency words.[6] The mean ERP amplitudes from each of these three time windows (see Table 3) were then examined with ANOVAs using word *frequency* (high vs. low), *hemisphere* (left = F3, C3, P3 vs. midline = Fz, Cz, Pz vs. right = F4, C4, P4), *lobe* (frontal = F3, Fz, F4 vs. central = C3, Cz, C4 vs. parietal = P3, Pz, P4), and saccade direction (left vs. right) as within-participant factors. (The Huynh–Feldt correction was once again applied as necessary to correct violations of sphericity; see Footnote 4.)

The ANOVA indicated a main effect of word frequency, $F(1,15) = 5.23$, $MS_e = 6.06$, $p < .05$, in the first interval (173–141 ms prior to saccade onset), with high-frequency words generating smaller amplitude positive-going ERP deflections than low-frequency words (.37 μV vs. 1.04 μV, respectively). There was also a reliable Frequency × Hemisphere interaction, $F(2,30) = 4.50$, $MS_e = .70$, $p < .05$, in the second interval (141–109 ms prior to saccade onset), with high-frequency words again generating smaller amplitude positive-going ERP deflections than the low-frequency words, but with this effect being limited to electrode Pz, $t(15) = 2.46$, $p < .05$, and marginal in electrode Cz, $t(15) = 1.81$, $p = .09$. This interaction also tended to become more pronounced over the left hemisphere, producing a Frequency × Lobe × Hemisphere interaction, $F(4,60) = 2.77$, $MS_e = .98$, $p < .05$, in the third interval (109–77 ms prior to saccade onset). Finally, although the main effect of saccade direction was reliable in the second interval, $F(1,15) = 5.53$, $MS_e = 19.06$, $p < .05$, and marginally reliable in the third, $F(1,15) = 3.41$, $MS_e = 48.62$, $p = .084$, saccade direction never interacted with word frequency (all Fs < 1).

The results of our second set of analyses (using saccade-aligned data) are consistent with previously published reports showing patterns of smaller amplitude positive-going waveforms

---

to zero in Equation 1. Likewise, because the centrally displayed words were always fixated, we decided to ignore the effect of visual acuity (i.e., eccentricity), which would have otherwise (slightly) increased the predicted familiarity-check times. These calculations resulted in the following predicted familiarity-check times: high-frequency words = 150 ms; low-frequency words = 163 ms. Finally, the predicted saccade-onset times were obtained by adding the mean predicted saccadic latency (= 125 ms) to the predicted familiarity-check times, resulting in the following predictions: for high-frequency words, saccadic latency = 275 ms; for low-frequency words, saccadic latency = 288 ms.

[6] Instead of using the predicted familiarity-check times that were obtained as described in Footnote 5, our predictions for these analyses were obtained by subtracting 125 ms (i.e., the time necessary to program a saccade, according to the E-Z Reader model; Pollatsek et al., 2006) from the mean *observed* saccade-onset times. We used this subtractive method for generating predictions because this allowed us to use the observed (and not the predicted) saccade-onset latencies, thereby reducing any prediction error that would be expected because the model's parameter values were chosen to fit the data from another experiment (Schilling et al., 1998). The mean predicted familiarity-check times were as follows: for high-frequency words, familiarity check = 150 ms; for low-frequency words, familiarity check = 178 ms.

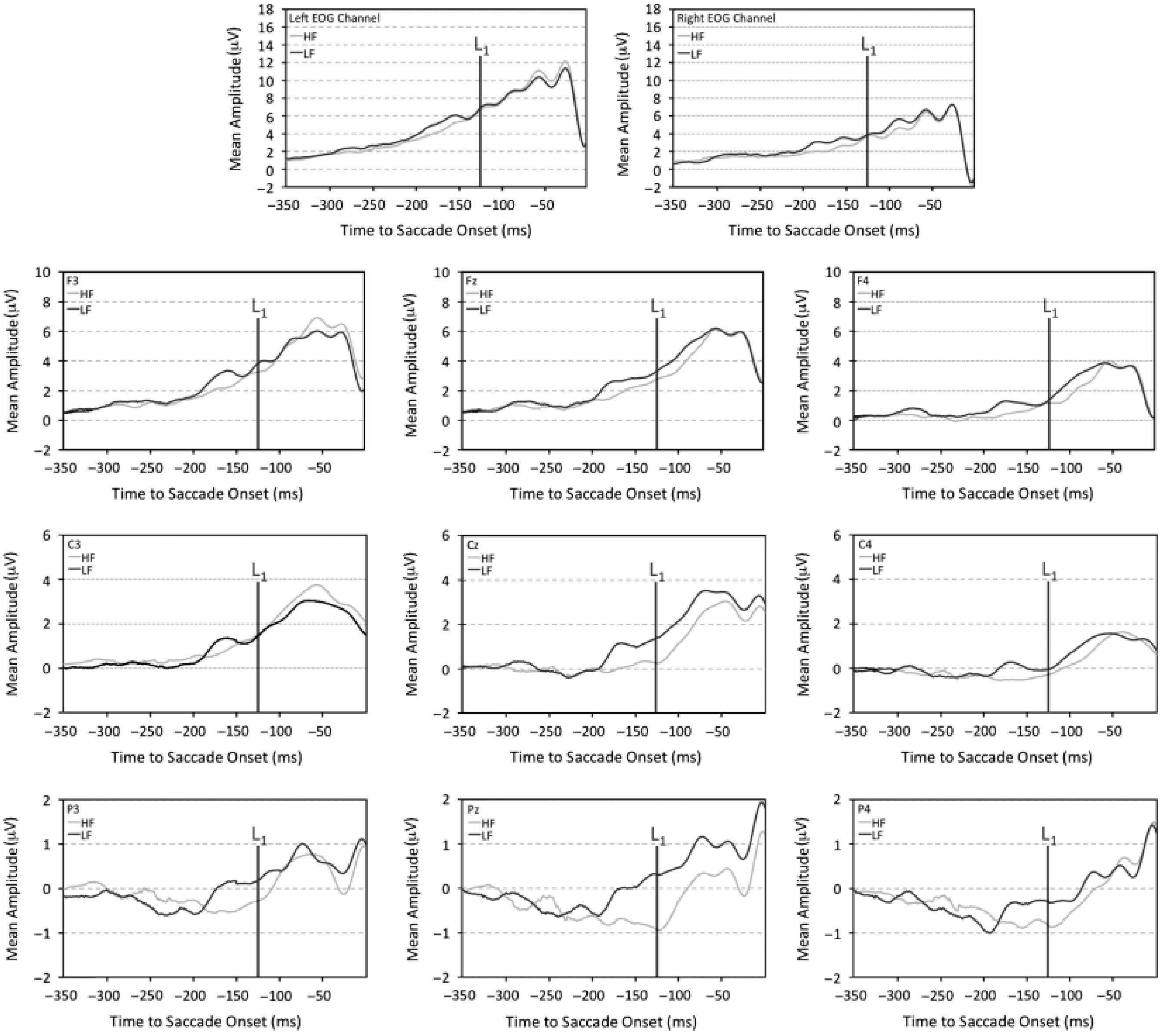

Figure 5. Grand-average waveforms for high- (HF) and low-frequency (LF) words from the left and right electrooculographic (EOG) channels and the nine channels used in our analyses (see Figure 2B). The waveforms are aligned to saccade onset and the mean time to complete the first stage of lexical processing in E-Z Reader (i.e., L_1, which occurs 125 ms before saccade onset) is indicated by the dark gray vertical line.

for high- as compared to low-frequency words (Hauk & Pulvermüller, 2004; Polich & Donchin, 1988; Sereno et al., 1998, 2003). The analyses also collectively indicate that frequency effects, which are robust and widely dispersed in the interval spanning 173 ms to 141 ms prior to saccade onset, become both weaker and more localized in the interval spanning 141 ms to 109 ms prior to saccade onset, and are almost absent in the interval spanning 109 ms to 77 ms prior to saccade onset. We will say more about the theoretical significance of this pattern in the General Discussion section.

General Discussion

This experiment identified ERP components that were modulated by a word's frequency of occurrence in printed text and are consistent with predictions (generated by the E-Z Reader model; Pollatsek et al., 2006; Reichle et al., 2006) about *when* these effects should occur relative to the onset of saccades that move the eyes from one word to another. Our analyses of the saccade-onset aligned data indicated that the effects of word frequency were evident well before saccade onset, suggesting that whatever lexical processing is modulated by word frequency occurs rapidly enough to leave an adequate amount of time (125–150 ms) to complete saccadic programming. The current results therefore provide some support for *the* core assumption of the E-Z Reader model of eye-movement control during reading: that the completion of an early stage of lexical processing, the familiarity check, is the "engine" that drives the forward progression of eye movements in normal reading.

Given these conclusions, how do the alternative interpretations of the familiarity check fare? Although the results of our

Table 3. *Mean ERP Amplitudes (in Microvolts, with Standard Errors of Means in Parentheses) as a Function of Three Time Intervals (in Millisecnods, Measured Prior to Saccade Onset), Word Frequency, and Electrode*

	Interval 1		Interval 2		Interval 3	
	(173–141 ms before saccade onset)		(141–109 ms before saccade onset)		(109–77 ms before saccade onset)	
Electrode	High-frequency words	Low-frequency words	High-frequency words	Low-frequency words	High-frequency words	Low-frequency words
F3	2.30	3.16	3.20	3.58	4.62	4.77
	(0.66)	(0.77)	(0.73)	(1.07)	(0.90)	(1.01)
Fz	2.03	2.74	2.67	3.25	3.74	4.65
	(1.01)	(0.90)	(0.98)	(1.14)	(1.08)	(1.13)
F4	0.56	1.17	1.05	1.33	1.86	2.80
	(0.57)	(0.60)	(0.61)	(0.74)	(0.75)	(0.80)
C3	0.90	1.27	1.53	1.45	2.67	2.34
	(0.43)	(0.57)	(0.60)	(0.78)	(0.82)	(1.02)
Cz	0.14	1.08	0.36	1.40	1.41	2.47
	(0.55)	(0.71)	(0.81)	(0.84)	(1.15)	(1.02)
C4	– 0.50	0.13	– 0.27	0.01	0.26	0.84
	(0.37)	(0.49)	(0.55)	(0.65)	(0.83)	(0.81)
P3	– 0.50	0.11	– 0.27	0.21	0.43	0.55
	(0.47)	(0.52)	(0.64)	(0.66)	(0.93)	(0.74)
Pz	– 0.74	0.01	– 0.86	0.30	– 0.14	0.64
	(0.41)	(0.64)	(0.69)	(0.70)	(1.04)	(0.81)
P4	– 0.81	– 0.34	– 0.79	– 0.29	– 0.45	– 0.12
	(0.34)	(0.54)	(0.56)	(0.55)	(0.85)	(0.73)

experiment are compatible with an interpretation of the familiarity check in which this process is based on some sort of rapidly available feeling of recognition (Atkinson & Juola, 1973; Yonelinas, 2002), the results are also congruent with the interpretation of the familiarity check as being based on a rapidly available stage of (pre)lexical processing, such as the processing that is necessary to convert the visual features of words into abstract orthographic codes.

The latter interpretation is consistent with a recent eye-tracking experiment (Reingold & Rayner, 2006) that demonstrated that the first-fixation duration on a word (which, according to E-Z Reader, is a fairly accurate index of how long it takes to complete the familiarity check; Reingold, 2003) is affected by manipulations that influence the visual quality of a word (e.g., degraded font). These results provide evidence that an early stage of lexical processing is affecting the ''decision'' about when to move the eyes. As discussed by Reichle and Laurent (2006), one hypothesis is that readers, through years of formal education and practice, come to learn the relationship between visual and/or orthographic cues and the time required to access meaning and then use these learned contingencies to program their eye movements in an efficient manner. We are currently testing this hypothesis, using a training regimen in conjunction with a paradigm similar to the one reported in this article to determine what kinds of lexical information (e.g., word form vs. meaning) might contribute to the development of the familiarity check mechanism that allows one to rapidly move one's eyes from a word (Vanyukov, Tokowicz, Reichle, & Perfetti, 2011).

REFERENCES

Atkinson, R. C., & Juola, J. F. (1973). Factors influencing speed and accuracy of word recognition. In S. Kornblum (Ed.), *Attention and performance IV* (pp. 583–611). New York: Academic Press.

Baccino, T., & Manunta, Y. (2005). Eye-fixation related potentials: Insight into parafoveal processing. *Journal of Psychophysiology*, *19*, 204–215.

Balota, D. A., & Chumbley, J. I. (1984). Are lexical decisions a good measure of lexical access? The role of word frequency in the neglected decision stage. *Journal of Experimental Psychology: Human Perception and Performance*, *10*, 340–357.

Becker, W., & Jürgens, R. (1979). An analysis of the saccadic system by means of double step stimuli. *Vision Research*, *19*, 967–983.

Clark, V. P., Fan, S., & Hillyard, S. A. (1995). Identification of early visual evoked potential generators by retinotopic and topographic analyses. *Human Brain Mapping*, *2*, 170–187.

Coles, M. G. H., & Rugg, M. D. (1995). Event-related brain potentials: An introduction. In M. Rugg & M. Coles (Eds.), *Electrophysiology of mind* (pp. 1–25). Oxford, UK: Oxford University Press.

Csibra, G., Johnson, M. H., & Tucker, L. A. (1997). Attention and oculomotor control: A high-density ERP study of the gap effect. *Neuropsychologia*, *35*, 855–865.

Csibra, G., Tucker, L. A., & Johnson, M. H. (1998). Neural correlates of saccade planning in infants: A high-density ERP study. *International Journal of Psychophysiology*, *29*, 201–215.

Dambacher, M., Kliegl, R., Hoffmann, M., & Jacobs, A. (2006). Frequency and predictability effects on event-related potentials during reading. *Brain Research*, *1084*, 89–103.

Ferree, T. C., Luu, P., Russell, G. S., & Tucker, D. M. (2001). Scalp electrode impedance, infection risk, and EEG data quality. *Journal of Clinical Neurophysiology*, *112*, 536–544.

Foxe, J. J., & Simpson, G. V. (2002). Flow of activation from V1 to frontal cortex in humans: A framework for defining ''early'' visual processing. *Experimental Brain Research*, *142*, 139–150.

Francis, W. N., & Kucera, H. (1982). *Frequency analysis of English usage: Lexicon and grammar*. Boston, MA: Houghton Mifflin.

Gehring, W., Goss, B., Coles, M., Meyer, D., & Donchin, E. (1993). A neural system for error detection and compensation. *Psychological Science*, *4*, 385–390.

Hauk, O., & Pulvermüller, F. (2004). Effects of word length and frequency on the human event-related potential. *Clincial Neurophysiology*, *115*, 1090–1103.

Heinzle, J., Hepp, K., & Martin, K. A. C. (2010). A biologically realistic cortical model of eye movement control in reading. *Psychological Review*, *117*, 808–830.

Henderson, J. M., & Ferreira, F. (1990). Effects of foveal processing difficulty on the perceptual span during reading: Implications for attention and eye movement control. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *16*, 417–429.

Hoffman, J. E., Simons, R. F., & Houck, M. R. (1983). Event-related potentials during controlled and automatic target detection. *Psychophysiology*, *20*, 625–632.

Jasper, H. H. (1958). The ten-twenty electrode system of the International Federation. *Electroencephalography and Clinical Neurophysiology*, *48*, 113–126.

Jennings, J. R. (1987). Editorial policy on analyses of variance with repeated measures. *Psychophysiology*, *24*, 474–475.

Joyce, C. A., Gorodnitsky, I. F., King, J. W., & Kutas, M. (2002). Tracking eye fixations with electroocular and electroencephalographic recordings. *Psychophysiology*, *39*, 607–618.

Just, M. A., & Carpenter, P. A. (1987). *The psychology of reading and language comprehension*. Boston, MA: Allyn & Bacon.

Kazai, K., & Yagi, A. (1999). Integrated effect of stimulation at fixation points on EFRP (eye-fixation related brain potentials). *International Journal of Psychophysiology*, *32*, 193–203.

Kliegl, R., Nuthmann, A., & Engbert, R. (2006). Tracking the mind during reading: The influence of past, present, and future words on fixation durations. *Journal of Experimental Psychology: General*, *135*, 12–35.

Kroll, J. F., & Merves, J. S. (1986). Lexical access for concrete and abstract words. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *12*, 92–107.

Leff, A. P., Scott, S. K., Rothwell, J. C., & Wise, R. J. S. (2001). The planning and guiding of reading saccades: A repetitive transcranial magnetic stimulation study. *Cerebral Cortex*, *11*, 918–923.

McConkie, G. W., Kerr, P. W., Reddix, M. D., & Zola, D. (1988). Eye movement control during reading: I. The location of the initial eye fixations on words. *Vision Research*, *28*, 1107–1118.

McPeek, R. M., Skavenski, A. A., & Nakayama, K. (2000). Concurrent processing of saccades in visual search. *Vision Research*, *40*, 2499–2516.

Molker, A., & Fischer, B. (1999). The recognition and correction of involuntary prosaccades in an antisaccade task. *Experimental Brain Research*, *125*, 511–516.

Mouchetant-Rostaing, Y., Gaird, H.-H., Bentin, S., Aguera, P.-E., & Pernier, J. (2000). Neurophysiological correlates of face gender processing in humans. *European Journal of Neuroscience*, *12*, 303–310.

Picton, T. W., Bentin, S., Berg, P., Donchin, E., Hillyard, S. A., Johnson, R. Jr., et al. (2000). Guidelines for using human event-related potentials to study cognition: Recording standards and publication criteria. *Psychophysiology*, *37*, 127–152.

Polich, J., & Donchin, E. (1988). P300 and the word frequency effect. *Electroencephalography and Clinical Neurophysiology*, *70*, 33–45.

Pollatsek, A., & Rayner, K. (1999). Is covert attention really unnecessary? *Behavioral and Brain Sciences*, *22*, 695–696.

Pollatsek, A., Reichle, E. D., & Rayner, K. (2006). Tests of the E-Z Reader model: Exploring the interface between cognition and eye-movement control. *Cognitive Psychology*, *52*, 1–56.

Rayner, K. (1979). Eye guidance in reading: Fixation locations within words. *Perception*, *8*, 21–30.

Rayner, K. (1998). Eye movements in reading and information processing: 20 years of research. *Psychological Bulletin*, *124*, 372–422.

Rayner, K., Ashby, J., Pollatsek, A., & Reichle, E. (2004). The effects of frequency and predictability on eye fixations in reading: Implications for the E-Z Reader model. *Journal of Experimental Psychology: Human Perception and Performance*, *30*, 720–732.

Rayner, K., & Duffy, S. (1986). Lexical complexity and fixation times in reading: Effects of word frequency, verb complexity, and lexical ambiguity. *Memory and Cognition*, *14*, 191–201.

Rayner, K., Li, X., & Pollatsek, A. (2007). Extending the E-Z Reader model of eye movement control to Chinese readers. *Cognitive Science*, *31*, 1021–1033.

Rayner, K., & Morrison, R. M. (1981). Eye movements and identifying words in parafoveal vision. *Bulletin of the Psychonomic Society*, *17*, 135–138.

Rayner, K., & Pollatsek, A. (1989). *The psychology of reading*. Englewood Cliffs, NJ: Prentice Hall.

Rayner, K., Pollatsek, A., Liversedge, S. P., & Reichle, E. D. (2009). Eye movements and non-canonical reading: Comments on Kennedy and Pynte (2008). *Vision Research*, *49*, 2232–2236.

Rayner, K., Slowiaczek, M. L., Clifton, C., & Bertera, J. H. (1983). Latency of sequential eye movements: Implications for reading. *Journal of Experimental Psychology: Human Perception and Performance*, *9*, 912–922.

Reichle, E. D. (2010). Serial attention models of reading. In S. P. Liversedge, I. D. Gilchrist, & S. Everling (Eds.), *Oxford handbook on eye movements*. Oxford, UK: Oxford University Press (in press).

Reichle, E. D., & Laurent, P. A. (2006). Using reinforcement learning to understand the emergence of "intelligent" eye-movement control during reading. *Psychological Review*, *113*, 390–408.

Reichle, E. D., Liversedge, S. P., Pollatsek, A., & Rayner, K. (2009). Encoding multiple words simultaneously in reading is implausible. *Trends in Cognitive Sciences*, *13*, 115–119.

Reichle, E. D., Pollatsek, A., Fisher, D. L., & Rayner, K. (1998). Towards a model of eye movement control in reading. *Psychological Review*, *105*, 125–157.

Reichle, E. D., Pollatsek, A., & Rayner, K. (2006). E-Z Reader: A cognitive-control, serial-attention model of eye-movement behavior during reading. *Cognitive Systems Research*, *7*, 4–22.

Reichle, E. D., Rayner, K., & Pollatsek, A. (2003). The E-Z Reader model of eye movement control in reading: Comparison to other models. *Brain and Behavioral Sciences*, *26*, 445–476.

Reichle, E. D., Vanyukov, P. M., Laurent, P. A., & Warren, T. (2008). Serial or parallel? Using depth-of-processing to examine attention allocation during reading. *Vision Research*, *48*, 1831–1836.

Reichle, E. D., Warren, T., & McConnell, K. (2009). Using E-Z Reader to model the effects of higher level language processing on eye movements during reading. *Psychonomic Bulletin & Review*, *16*, 1–21.

Reingold, E. M. (2003). Eye-movement control in reading: Models and predictions. *Behavioral and Brain Sciences*, *26*, 500–501.

Reingold, E. M., & Rayner, K. (2006). Examining the word identification stages hypothesized by the E-Z Reader model. *Psychological Science*, *17*, 742–746.

Salvucci, D. D. (2001). An integrated model of eye movements and visual encoding. *Cognitive Systems Research*, *1*, 201–220.

Schilling, H. E. H., Rayner, K., & Chumbley, J. I. (1998). Comparing naming, lexical decision, and eye fixation times: Word frequency effects and individual differences. *Memory and Cognition*, *26*, 1270–1281.

Sereno, S. C., Brewer, C. C., & O'Donnell, P. J. (2003). Context effects in word recognition: Evidence for early interactive processing. *Psychological Science*, *14*, 328–333.

Sereno, S. C., Rayner, K., & Posner, M. I. (1998). Establishing a timeline of word recognition: Evidence from eye movements and event-related potentials. *NeuroReport*, *9*, 2195–2200.

Treisman, A., & Gelade, G. (1980). A feature integration theory of attention. *Cognitive Psychology*, *12*, 97–136.

Van Rullen, R., & Thorpe, S. (2001). The time course of visual processing: From early perception to decision-making. *Journal of Cognitive Neuroscience*, *13*, 454–461.

Vanyukov, P. M., Tokowicz, N., Reichle, E. D., & Perfetti, C. A. (2011). *What is the familiarity check? Using event-related potentials to examine how orthographic, phonological, and semantic information affects eye-movement latencies*. Manuscript in preparation.

Vergilino, D., & Beauvillain, C. (2000). The planning of refixation saccades in reading. *Vision Research*, *40*, 3527–3538.

Yonelinas, A. P. (2002). The nature of recollection and familiarity: A review of 30 years of research. *Journal of Memory and Language*, *46*, 441–517.

Young, L., & Sheena, D. (1975). Survey of eye movement recording methods. *Behavior Research Methods and Instrumentation*, *7*, 397–429.

(Received March 9, 2010; Accepted November 13, 2010)