Research Report

Examining the Word Identification Stages Hypothesized by the E-Z Reader Model

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ABSTRACT—***A critical prediction of the E-Z Reader model is that experimental manipulations that disrupt early encoding of visual and orthographic features of the fixated word without affecting subsequent lexical processing should influence the processing difficulty of the fixated word without affecting the processing of the next word. We tested this prediction by monitoring participants' eye movements while they read sentences in which a target word was presented either normally or altered. In the critical condition, the contrast between the target word and the background was substantially reduced. Such a reduction in stimulus quality is typically assumed to have an impact that is largely confined to a very early stage of word recognition. Results were consistent with the E-Z Reader model: This faint presentation had a robust influence on the duration of fixations on the target word without substantially altering the processing of the next word.***

Over the past three decades, an intensive investigation of the nature of eye movement control during reading has generated a wealth of findings, as well as considerable controversy (Starr & Rayner, 2001). Recently, the theoretical focus in this field has shifted away from qualitative models and toward quantitative implemented models. This shift was primarily driven by the introduction of a formal computational model, named the *E-Z Reader* model (Reichle, Pollatsek, Fisher, & Rayner, 1998). This model, and its subsequent revisions (Pollatsek, Reichle, & Rayner, 2003, 2006; Rayner, Ashby, Pollatsek, & Reichle, 2004; Reichle, Rayner, & Pollatsek, 1999, 2003), has successfully accounted for empirical findings concerning a wide range of reading phenomena and has sparked the formulation of rival models such as SWIFT (Engbert, Longtin, & Kliegl, 2002; Engbert, Nuthmann, Richter, & Kliegl, 2005) and Glenmore (Reilly & Radach, 2003).

The main goal of the present study was to test a novel empirical prediction of the E-Z Reader model. Specifically, as argued by Reingold (2003), a critical prediction of this model is that experimental manipulations that disrupt early encoding of visual and orthographic features of the fixated word (word n) without affecting subsequent lexical processing of that word should influence the processing difficulty of word n without affecting the processing of the next word (word $n + 1$). Figure 1 illustrates this prediction by contrasting several different models' assumptions concerning the length of the interval during which the eyes are fixated on word n and the reader is parafoveally processing word $n + 1$. It is important to note that the duration of this interval, referred to as the parafoveal preview, is expected to determine the magnitude of any processing benefit when word $n + 1$ is fixated later (e.g., longer preview resulting in shorter fixations on word $n + 1$).

The first model shown in Figure 1 was proposed by Morrison (1984) and was an important precursor to the E-Z Reader framework. Morrison's model assumes that attention shifts in the direction of the next saccade prior to execution of the saccade. Specifically, attention is initially centered on the foveated word. Following the identification of this word, attention covertly shifts in the direction of reading, and a saccade aimed at fixating the newly attended word is programmed. Thus, according to

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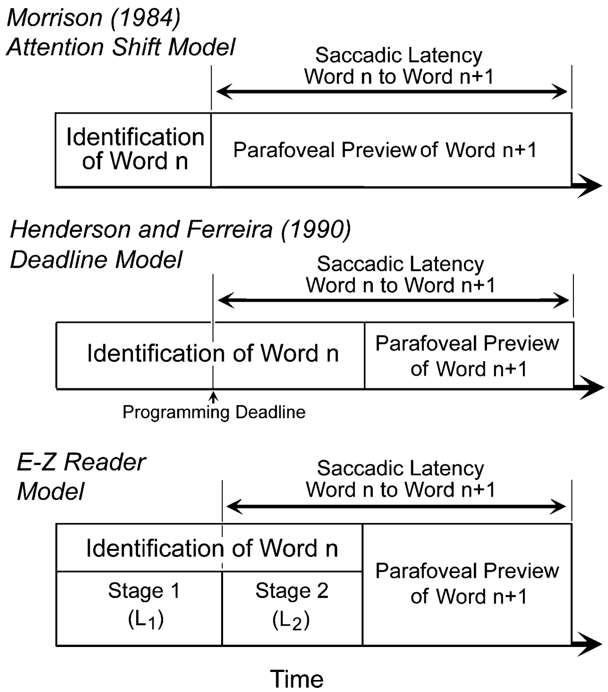

Fig. 1. Illustration of the assumptions of three models concerning the length of the interval during which the eyes are fixated on word *n* and the reader is parafoveally processing word *n* + 1 (see the text for details).

Morrison's *attention-shift* model, the identification of word *n* simultaneously triggers both the deployment of attention and the programming of a saccade toward word *n* + 1. Consequently, in this model, the duration of the parafoveal preview is equivalent to the saccadic programming time, which is totally independent of the characteristics of word *n*. Thus, Morrison's model is unable to account for results obtained in subsequent studies demonstrating an influence of variables such as the frequency and predictability of word *n* on the subsequent processing of word *n* + 1 (e.g., Balota, Pollatsek, & Rayner, 1985; Drieghe, Rayner, & Pollatsek, 2005; Henderson & Ferreira, 1990; Inhoff, Pollatsek, Posner, & Rayner, 1989; Kennison & Clifton, 1995; Rayner & Duffy, 1986; Rayner, Sereno, Morris, Schmauder, & Clifton, 1989; Rayner & Well, 1996; White, Rayner, & Liversedge, 2005a, 2005b).

To correct for this deficiency, Henderson and Ferreira (1990) proposed modifying Morrison's (1984) model by adding the concept of a saccadic programming deadline. In cases in which word *n* is easily identified, this deadline does not come into effect, and as is the case with Morrison's model, the duration of the parafoveal preview of word *n* + 1 is equivalent to the saccadic programming time. However, as shown in Figure 1, when identification of word *n* extends beyond the deadline, the programming of the saccade from word *n* to word *n* + 1 is initiated, and the duration of the parafoveal preview of word *n* + 1 is reduced by the interval between the deadline and the completion of identification of word *n*. Consequently, according to Henderson and Ferreira, any variable that substantially increases the difficulty of identifying word *n* would invariably result in a decrease in the parafoveal preview of word *n* + 1, and a concomitant decrease in the magnitude of any processing benefit when word *n* + 1 is later fixated.

As illustrated in Figure 1, in the E-Z Reader model, the duration of parafoveal preview of word *n* + 1 is determined by the following three core aspects of this model. First, the E-Z Reader model introduces a distinction between two stages of lexical processing: an early stage (L_1), which includes the extraction and identification of the orthographic form of the word, and a later stage (L_2), which is solely involved with processing at the phonological and semantic level. Second, the programming of a saccade to the next word (word *n* + 1) is initiated following the completion of L_1 processing of word *n*. Third, parafoveal preview of word *n* + 1 begins following the completion of L_2 processing of word *n*. Thus, according to the E-Z Reader model, variation in the duration of L_2 processing of word *n*, $t(L_2)$, critically determines the duration of parafoveal preview of word *n* + 1. As shown in Figure 1, the duration of the parafoveal preview of word *n* + 1 equals the duration of the interval between the initiation and execution of the saccade to word *n* + 1 minus $t(L_2)$ of word *n*. Thus, according to the E-Z Reader model, experimental manipulations of the characteristics of word *n* (e.g., word frequency and predictability) should have an effect on the subsequent processing of word *n* + 1 if and only if those manipulations influence L_2 processing of word *n*. Variables influencing L_1, but not L_2, processing of word *n*, although they modulate the difficulty of the lexical processing of word *n*, should not affect the magnitude of any processing benefit when word *n* + 1 is later fixated.

Although the distinction between L_1 and L_2 proposed by the E-Z Reader model has not been fully specified, it is by definition the case that L_1 processes are completed prior to the initiation of L_2 processes. Therefore, in attempting to select an experimental manipulation that would be likely to influence L_1 but not L_2 processes, it makes sense to consider variables that are assumed to have an impact confined to the earliest stage of lexical processing. One such manipulation, reducing *stimulus quality*, involves reducing the contrast of letter strings and is assumed to disrupt an early stage of word recognition in which visual features are encoded and abstract letter identities are computed (see Besner & Roberts, 2003; Reynolds & Besner, 2004). Thus, according to this model, stimulus quality should influence L_1, but not L_2, processing. Therefore, in the present study, we examined the influence of a substantial reduction in the stimulus quality of word *n* (the *faint* condition) on subsequent processing of word *n* + 1. Two additional manipulations of word *n* were used: case alternation (the *case-alternation* condition) and boldface type (the *boldface* condition). Unlike stimulus quality, case alternation has been shown to influence postencoding lexical processing (Besner & McCann, 1987; Herdman, Chernecki, & Norris, 1999) and attentional processing (Mayall, Humphreys, Mechelli, Olson, & Price, 2001). The use of boldface type may also influence attentional or postlexical processing. Consequently, the case-alternation and boldface manipulations of word *n* would be expected to lengthen L_2 processing and to increase fixation durations on word *n* + 1. However, our primary prediction was that the faint manipulation would lengthen the fixation duration for word *n*, but have little effect on the fixation duration for word *n* + 1.

METHOD

Participants

Forty-eight undergraduate students at the University of Toronto, Canada, were tested. They were all native English speakers and were paid $10.00 (Canadian) per hour.

Materials and Design

Forty-eight pairs of sentences were used in the experiment. The sentences in each pair contained the same adjective as word *n* and two different nouns that were equated on word length and word frequency as word *n* + 1. In half of the sentences (24 pairs), word *n* + 1 was a five-letter word, and in the other half, it was a six-letter word. The average length of word *n* was 6.3 characters. The average frequency of word *n* + 1 was 41 per million, and the average frequency of word *n* was 198 per million (Francis & Kucera, 1982). For each participant, one sentence in each pair was unmodified. Word *n* in the other sentence in each pair was modified in one of three ways: presented in boldface type, shown with severely reduced contrast, or shown with case alternation. In addition, 12 practice sentences (4 per condition) were read at the beginning of the experiment. The order of sentence presentation was randomized for each participant, and the assignment of sentences to conditions was counterbalanced across participants.

Apparatus and Procedure

Eye movements were measured with an SR Research EyeLink II system. Following calibration, gaze-position error was less than 0.5°.

The sentences were displayed on a single line on a ViewSonic 17PS monitor. All letters were lowercase (except when capitals were appropriate) and in a mono-spaced Courier font. The text was presented in black (4.7 cd/m^2) on a white background (56.8 cd/m^2). The average brightness of word *n* in the faint condition was 46.9 cd/m^2. Participants were seated 60 cm from the monitor, and 2.4 characters equaled 1° of visual angle.

Participants were instructed to read the sentences for comprehension. After reading each sentence, they pressed a button to end the trial and proceed to the next sentence.

RESULTS

For both word *n* and word *n* + 1, a number of standard eye movement measures (Rayner, 1998) were examined in the data

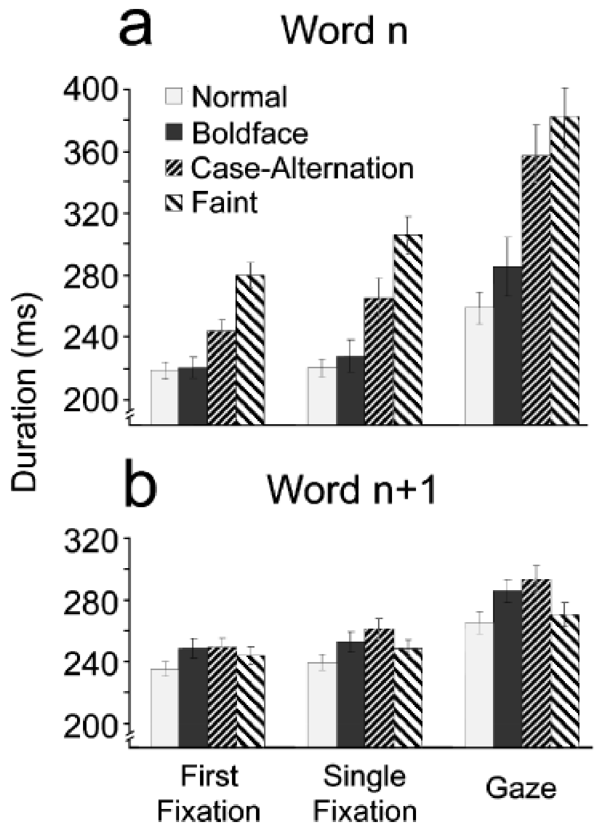

Fig. 2. First-fixation duration, single-fixation duration, and gaze duration on (a) word *n* and (b) word *n* + 1 as a function of experimental condition.

analyses (see Fig. 2). Specifically, the following measures were analyzed: (a) first-fixation duration (i.e., the duration of the first forward fixation on a target word independent of the number of fixations made on the word), (b) single-fixation duration (i.e., the duration of the fixation on the target word when the word was initially encountered in cases in which only a single forward fixation was made on that word), and (c) gaze duration (i.e., the aggregate duration of all fixations on a target word when it was initially encountered, prior to a saccade to another word). In computing these measures, we excluded a total of 19.9% of trials for one or more of the following four reasons: (a) Word *n* was skipped (6.0% of trials), (b) word *n* + 1 was skipped (4.5% of trials), (c) the participant made a regression from word *n* (7.2% of trials), or (d) the participant made a regression from word *n* + 1 (3.9% of trials). Planned comparisons by participants and by items were performed across the four experimental conditions (normal, boldface, case-alternation, faint) for both word *n* and word *n* + 1 (for all comparisons, $df = 47$).[1]

[1]We also examined the influence of the typographical modifications of word *n* on the fixation just prior to the first fixation on word *n*. Duration of this prior fixation did not vary significantly as a function of condition (normal: 209 ms, boldface: 215 ms, case-alternation: 213 ms, faint: 216 ms).

TABLE 1
Probability of a Single Forward Fixation on Word* n *and Means of Fixation Measures for Word* n *+ 1 for Trials in Which a Single Forward Fixation on Word* n *Occurred

Condition	Word n: probability of single fixation	Word $n + 1$: First-fixation duration (ms)	Word $n + 1$: Single-fixation duration (ms)	Word $n + 1$: Gaze duration (ms)
Normal	.814 (.019)	236 (5.442)	242 (6.365)	267 (7.802)
Boldface	.754 (.029)	245 (6.984)	252 (7.615)	293 (10.37)
Case-alternation	.582 (.030)	248 (7.317)	265 (7.637)	299 (8.654)
Faint	.642 (.034)	243 (6.833)	252 (7.287)	272 (8.674)

Note. Standard errors are given in parentheses.

Word *n*

Typographical modifications of word n increased the fixation durations for that word (see Fig. 2a). As the data patterns for first-fixation duration and single-fixation duration indicate, when word n was first encountered, the faint manipulation produced dramatically longer fixation durations than either the case-alternation manipulation or the boldface manipulation (all t_1s > 4.99, ps $< .001$, ds > 1.03; all t_2s > 7.10, ps $< .001$, ds > 1.46). This difference between the faint condition and the latter two conditions was still apparent, but somewhat attenuated, in the gaze-duration measure (all t_1s > 2.35, ps $< .05$, ds $> .49$; all t_2s > 2.74, ps $< .01$, ds > 0.57). In addition, the case-alternation manipulation produced a substantial disruption of processing, resulting in increased durations for all fixation measures (all t_1s > 5.34, ps $< .001$, ds > 1.10; all t_2s > 5.34, ps $< .001$, ds > 1.10). In contrast, the boldface manipulation produced only a minor disruption, as indicated by the absence of an effect on either first-fixation duration or single-fixation duration (all ts < 1) and the small effect on gaze duration, $t_1 = 2.18$, $p < .05$, $d = 0.45$; $t_2 = 3.21$, $p < .01$, $d = 0.66$.

Word *n* + 1

Figure 2b displays the results for word $n + 1$. In marked contrast to the results for word n, the faint manipulation of word n had very minimal influence on the duration of fixations on word $n + 1$. Specifically, there was no significant effect on gaze duration, $t_1 = 1.16$, $p = .25$, $d = 0.23$; $t_2 = 1.14$, $p = .26$, $d = 0.23$, and there was only a marginally significant effect on first-fixation and single-fixation durations (both t_1s > 1.92, ps $> .06$, ds > 0.39; both t_2s > 2.46, ps $< .05$, ds > 0.50).[2] Case alternation produced a significant increase in first-fixation duration, $t_1 = 3.42$, $p < .001$, $d = 0.71$; $t_2 = 4.15$, $p < .001$, $d = 0.86$; single-fixation duration, $t_1 = 5.11$, $p < .001$, $d = 1.05$; $t_2 = 7.25$, $p < .001$, $d = 1.50$; and gaze duration, $t_1 = 4.88$, $p < .001$, $d = 1.01$; $t_2 = 6.17$, $p < .001$, $d = 1.27$. Similarly, the boldface manipulation produced a significant increase in first-fixation duration, $t_1 = 3.05$, $p < .01$, $d = 0.63$; $t_2 = 3.42$, $p < .001$, $d = 0.71$; single-fixation duration, $t_1 = 2.56$, $p < .05$, $d = 0.53$; $t_2 = 3.70$, $p < .001$, $d = 0.76$; and gaze duration, $t_1 = 4.45$, $p < .001$, $d = 0.93$; $t_2 = 4.83$, $p < .001$, $d = 0.99$. Both the boldface manipulation, $t_1 = 2.10$, $p < .05$, $d = 0.43$; $t_2 = 2.53$, $p < .05$, $d = 0.52$; and the case-alternation manipulation, $t_1 = 3.41$, $p < .001$, $d = 0.70$; $t_2 = 3.71$, $p < .001$, $d = 0.77$; produced significantly longer gaze durations for word $n + 1$ than the faint manipulation.

Given that the pattern of the parafoveal processing of word $n + 1$ may be more complex when there are multiple fixations on word n, we present in Table 1 the fixation durations for word $n + 1$ for those trials on which word n was fixated only once. An analysis using these conditionalized data produced results that were qualitatively very similar to the results of the overall analysis just reported (cf. Table 1 and Fig. 2b).

DISCUSSION

The results were consistent with the critical prediction of the E-Z Reader model: A substantial reduction in the stimulus quality of word n (i.e., the faint manipulation) had a robust effect on the duration of fixations on that word without substantially altering the processing of word $n + 1$. This finding is also consistent with the notion that stimulus quality, a variable influencing early word recognition processes, has an impact on the L_1 stage, but not the L_2 stage, of word identification. More generally, the present experiment demonstrated a dramatic double dissociation between the influence of variables on the processing of word n and word $n + 1$. Specifically, the faint manipulation had the strongest influence on the processing of word n and only a very negligible influence on the processing of word $n + 1$. In contrast, compared with the faint manipulation, the boldface and case-alternation manipulations had stronger influences on the processing of word $n + 1$ and substantially weaker influences on the processing of word n.

This type of dissociation is clearly incompatible with the deadline hypothesis proposed by Henderson and Ferreira (1990), because the deadline concept predicts that the strength

[2]The pattern of a marginally significant effect of the faint manipulation on first-fixation duration coupled with no significant effect of this manipulation on gaze duration is partly due to the higher-than-normal probability of a single fixation on word $n + 1$ in the faint condition (normal: .836, faint: .882).

of the influence of variables on the processing of word *n* should be monotonically related to their impact on the processing of word *n* + 1. Indeed, the E-Z Reader model uniquely predicts the present results, and we suspect that these findings pose a nontrivial challenge to all other models of eye movement control in reading.

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