Eye Movement Control in Reading: A Comparison of Two Types of Models

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Two classes of models have been proposed to account for eye movement control during reading. Proponents of the 1st class of model claim that the decision of when to move the eyes (reflected in fixation duration) is primarily influenced by the status of on-line language processing such as lexical access. Supporters of the 2nd class of model, however, maintain that (a) lower level oculomotor factors such as fixation location govern the decision of when to move the eyes and (b) lexical variables exert only a weak influence. In this study, fixation duration on low- and high-frequency target words was examined as a function of fixation location and the number of fixations on a target word. The data are inconsistent with an oculomotor model.

Understanding how eye movements are controlled in reading is vitally important in devising a model of skilled reading (see Rayner & Pollatsek, 1989). It is not surprising, then, that there has been considerable interest in this topic over the past 20 years. Many of the early investigations of eye movement control in reading focused on the extent to which moment-to-moment processes control the movement of the eyes (Bouma & deVoogd, 1974; Hochberg, 1975; O'Regan, 1979; Pollatsek & Rayner, 1982; Rayner, 1978, 1979; Rayner & McConkie, 1976; Rayner & Pollatsek, 1981). The general conclusion that emerged was that where readers look next (fixation location) and when they move to a new location (fixation duration) are independent processes, but they are both on-line decisions (Rayner & Pollatsek, 1987, 1989).

In this article, we focus on the decision regarding when to move the eyes. We begin, however, by reviewing the research concerning the decision about where to move the eyes. Whether these decisions are, in fact, independent of each other is the distinguishing feature between two different classes of models of eye movement control. One type of model holds that the where and when decisions are independent. Crucially, it claims that the when decision is affected by linguistic variables, and hence, fixation durations should reflect, on-line, the processing complexities of language. The other type of model asserts that lower level oculomotor or visuomotor factors largely determine when the eyes move. That is, where the eyes are fixated in a particular word, for example, affects how long the eyes remain fixated. Thus, although the where and when decisions may be made at different times, the when decision depends on the outcome of the where decision. It is in this sense that the where and when decisions in an oculomotor model are not independent. We discuss these two classes of models in more detail after presenting the research findings concerning the where and when decisions.

Where to Fixate Next

A great deal of research indicates that fixation locations within words in text are determined by low-level visual information obtained from the prior fixation in parafoveal vision. It has been demonstrated that, for example, when word length information about the subsequent word is not available, readers saccade (move their eyes) a shorter distance than when such information is available (McConkie & Rayner, 1975; Morris, Rayner, & Pollatsek, 1990; Pollatsek & Rayner, 1982; Rayner & Bertera, 1979; Rayner & Pollatsek, 1981). Also, the length of the parafoveal word has been shown to strongly influence the (eventual) location of a fixation in that word and, hence, the length of the saccade into that word (Blanchard, Pollatsek, & Rayner, 1989; O'Regan, 1979, 1980, 1981; Rayner, 1979).

The location of the initial fixation within an individual word, the landing position, is somewhat systematic in that readers tend to fixate about halfway between the beginning and the middle of words (Dunn-Rankin, 1978; McConkie, Kerr, Reddix, & Zola, 1988; O'Regan, 1981; Radach & Kempe, 1993; Rayner, 1979; Vitu, O'Regan, Inhoff, & Topolski, 1995; Vitu, O'Regan, & Mittau, 1990). Rayner...
(1979) originally labeled this prototypical location as the preferred viewing location. Subsequently, O’Regan and Levy-Schoen (1987) distinguished between the preferred viewing location and what O’Regan and colleagues now refer to as the optimal viewing position. The optimal viewing position is the location in a word at which recognition time is minimized. It turns out to be a bit to the right of the preferred viewing location, closer to the center of the word.

Extensive research efforts have examined the consequences of making fixations at locations other than this optimal viewing position (McCOnkie, Kerr, Reddix, Zola, & Jacobs, 1989; Nazir, 1993; O’Regan, Levy-Schoen, Pynte, & Brugallere, 1984; Vitu, 1991, 1993; Vitu et al., 1990). For words presented in isolation, two general effects have been found. First, there is what we refer to as a refixation effect: The further the eyes are from the optimal viewing position, the more likely it is that a refixation will be made on the word. Second, there is what we refer to as the processing-cost effect: There is a cost in fixation time associated with fixations at locations other than the optimal viewing position. For every letter that the participant’s fixation deviates from the optimal viewing position, the associated cost amounts to about 20 ms (e.g., O’Regan et al., 1984). When words are presented in text, however, although the refixation effect remains, the processing costs are far less serious (e.g., Vitu et al., 1990). This result suggests that contextual information may override low-level visual processing constraints and/or that in reading-connected discourse, the information acquired about a word before it is directly fixated affects its later fixation location and duration.

According to O’Regan and Levy-Schoen (1987), the reason that readers typically fixate the preferred viewing location instead of the optimal viewing position (i.e., fixate farther to the left) is because of oculomotor noise in saccade programming and execution. They cited a study by Coeffe and O’Regan (1987; see also Findlay, 1982) in which participants were required to make saccades of about 3.5° to 10° to a fixation target marked by crosses within a string of nine double-spaced letters. Coeffe and O’Regan found that participants’ saccades overshot closer targets, undershot farther targets, but were accurate for targets located between the beginning and middle of the letter string (i.e., the preferred viewing location). When single letters were presented as targets, participants’ saccades were accurate to all locations, showing that the presence of surrounding letters influences saccade accuracy. Coeffe and O’Regan were able to improve participants’ accuracy for targets within letter strings by making the target location more predictable or by increasing the duration of the presaccade fixation. Although these manipulations may have aided participants in perceptually isolating the target within the string, the greatest accuracy attained was still at a location to the left of the center of the string (when it was to the right of fixation).

Another explanation for why readers tend to fixate the preferred viewing location, as opposed to the optimal viewing position, may be related to parafoveal processing during fixations in reading. A large body of data has investigated the parafoveal preview benefit; when the reader fixates word $n$, information is obtained parafoveally about word $n+1$, which facilitates its subsequent (foveal) processing (Balota, Pollatsek, & Rayner, 1985; Blanchard et al., 1989; Brihl & Inhoff, 1995; Henderson & Ferreira, 1990; Inhoff, 1989a, 1989b, 1990; Inhoff & Rayner, 1986; Kennison & Clifton, 1995; Lima & Inhoff, 1985; Morris et al., 1990; Pollatsek, Lesch, Morris, & Rayner, 1992; Pollatsek, Rayner & Balota, 1986; Rayner, 1975, 1986; Rayner, Balota, & Pollatsek, 1986; Rayner, Well, Pollatsek, & Bertera, 1982). Consequently, when preview of the parafoveal word is available, however, later fixation time on that word is significantly longer. When only the first few letters of the parafoveal word are available, however, later fixation time on that word is comparable with a full preview. The results of these studies suggest that readers often move their eyes to a position in a following word at or beyond the margin from which information was obtained parafoveally in the previous fixation. For example, if the first two or three letters of an eight-letter word were identified parafoveally on the prior fixation, the reader’s ensuing fixation might then be on the third or fourth letter of that word.

A given fixation location, however, can be viewed not only as a landing position in a word (as discussed above), but also as a takeoff point or launch site to the next word. It has been demonstrated that one launch site is related to the next landing position (McCOnkie et al., 1988; Radasch & Kempe, 1993). Although the average landing position in a word lies between the beginning and middle of a word, this position varies as a function of the distance from the prior launch site. For example, if the distance to a target word is large (8 to 10 letter spaces), the landing position is shifted to the left. Likewise, if the distance is small (2 to 3 letter spaces), the landing position is shifted to the right.

It would seem that an optimal strategy for readers would be to make successive fixations word-by-word, landing near the middle of each word as they read. However, readers sometimes refixate words (i.e., make two consecutive fixations on the same word), particularly when the word is long or linguistically complex. Readers also skip words, especially short words, inasmuch as they are often identified on a prior fixation (Blanchard et al., 1989; Rayner, 1979; Vitu et al., 1995). Factors such as these result in a distribution of...
launch sites and, hence, landing positions (McConkie et al., 1988; Radach & Kempe, 1993).

A final issue with respect to the where decision is whether semantic information from a parafoveal word influences the subsequent landing position in that word. Underwood and colleagues examined the landing position in long words (10 or more letters) composed of informative and redundant halves (Everatt & Underwood, 1992; Hyona, Niemi, & Underwood, 1989; Underwood, Bloomfield, & Clews, 1988; Underwood, Clews, & Everatt, 1990). They reported that the eyes move farther into a word when the informative portion is located at the end rather than the beginning of the word. Rayner and Morris (1992), however, raised some theoretical and methodological problems with those experiments and attempted to replicate the prior findings. Neither they nor Hyona (1995) replicated the effect. At this point, it seems prudent to assume that semantic preprocessing of this sort does not occur (see Balota & Rayner, 1991, for a review of word recognition processes in reading that can occur foveally and parafoveally).

When to Move the Eyes

What determines when we move our eyes? This question is at the heart of the current controversy concerning different types of models of eye movement control in reading. We describe these models in the next section. We review first some relevant data.

It is important to note that during reading, information gets into the processing system very early in a fixation, leaving considerable time for processes associated with word recognition and text comprehension. One paradigm that has been used is predicting a foveal mask during reading, displayed at various intervals after fixation onset (Ishida & Ikeda, 1989; Rayner, Inhoff, Morrison, Slowiaczek, & Bertera, 1981; Slowiaczek & Rayner, 1987). These studies demonstrated that, if the text is exposed for about 50 ms on each fixation before being masked, reading proceeds quite normally. If the mask occurs earlier, however, reading is disrupted. Although readers can acquire the information necessary for reading in the first 50 ms of fixations, they continue to extract information at other times during fixations as well (see, e.g., Blanchard, McConkie, Zola, & Wolverton, 1984).

The past 20 years of eye movement research have yielded considerable data demonstrating that various lexical, syntactic, and discourse factors do influence fixation times on words (for recent reviews, see Rayner, 1995; Rayner & Sereno, 1994). There is evidence that fixation time is affected on-line by the following variables: word frequency, lexical ambiguity, semantic relationship, contextual constraint, syntactic complexity, anaphora, and coreference. It thus seems reasonable to conclude that linguistic variables are involved in the decision about when to move the eyes. However, some researchers have argued that lower level oculomotor factors are primarily responsible for controlling eye movements (see O'Regan, 1990, 1992). We will examine this debate more closely in considering specific proposals of eye movement control in reading.

Models of Eye Movement Control

Although many proposals for eye movement control in reading have been suggested, for simplicity we classify them into two general categories: (a) those that assign lexical processing or other ongoing comprehension processes a paramount role in influencing eye movements, versus (b) those that maintain that eye movements are mainly controlled by oculomotor factors and are only indirectly related to ongoing language processing. The first category includes a model proposed by Morrison (1984), with various modifications (Henderson & Ferreira, 1990; Kennison & Clifton, 1995; Pollatsek & Rayner, 1990; S. C. Sereno, 1992), as well as one proposed by Just and Carpenter (1980). The second category includes the strategy-tactics model (O'Regan, 1990, 1992; O'Regan & Levy-Schoen, 1987), as well as proposals of Kowler and Anton (1987) and McConkie et al. (1988, 1989). We will provide overviews of Morrison's and of O'Regan's models.

Morrison's Model

In Morrison's (1984) model, at the beginning of each fixation, eye gaze and visual attention are oriented to the same location: the foveal word (word n). After foveal word processing has reached a criterion level (perhaps some stage of lexical access), attention shifts to the parafoveal word (word n + 1) during the fixation. This shift of attention allows processing of word n + 1 to begin and also signals the eye movement system to prepare a motor program for an eye movement to the newly attended location. Once the motor program is completed, it is executed and the eyes then saccade to the new word. Because there is a lag between the attentional shift and saccade execution due to programming latency, information continues to accumulate from the parafoveal word before it is directly fixated. If the parafoveal word is identified quickly, attention shifts again to the word beyond the parafoveal word (word n + 2) before the eye movement is fully programmed. In this case, the eyes saccade to word n + 2, skipping word n + 1. Usually there is a cost in modifying the motor program, and the duration of the fixation prior to a skip is consequently inflated (see, e.g., Hogaboam, 1983; Pollatsek et al., 1986). If the motor program is too far advanced, however, there will be either (a) a short fixation on word n + 1 followed by a longer fixation on word n + 2 or (b) a fixation located at an intermediate position between words n + 1 and n + 2. The model thus can explain some rather puzzling aspects of eye movement behavior in reading: for example, very short fixations in text (given that saccadic latency in simple oculomotor tasks is typically on the order of 175 to 200 ms) and unusual landing sites (e.g., the space between words).

One problem in Morrison’s model in its original form (Morrison, 1984) is that there is no explanation for why words are sometimes refixated. That is, if lexical access is

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5 Morrison’s model was heavily influenced by Becker and Jurgens’s (1979) work.
the sole trigger for attentional shifts (and, hence, eye movements), words should never be refixated. Some recent modifications of Morrison's model (e.g., Henderson & Ferreira, 1990; S. C. Sereno, 1992) incorporate a deadline for programming an eye movement; if lexical processing has not reached a criterion level by this deadline, attention does not shift from the current word and it may be refixated. Another account of why words are refixated, proposed by Pollatsk and Rayner (1990), does not involve any type of deadline. Rather, Pollatsk and Rayner suggested that the signal to stay on a word may be related to a decision that something does not fully compute; for example, the word that has been accessed may not fit into the syntactic or semantic structure of the sentence being constructed. These models do not necessarily claim that lexical effects will not occur in the first fixation of refixated words; they merely state that lexical processing may not be complete enough to warrant an attentional shift to the following word.

O'Regan's Model

According to O'Regan's (1990, 1992; O'Regan & Levy-Schoen, 1987) strategy–tactics model, the eyes' initial landing position in a word largely determines how long they remain fixated and where the following fixation is made. O'Regan proposed that readers adopt a global strategy (e.g., careful or risky reading) that coarsely influences fixation times and saccade lengths. He also proposed that readers implement local, within-word tactics that are based on lower level, nonlexical information available early in a fixation. It is the operation and control of these within-word tactics that are most relevant to the current debate. If the eyes land in a region of a word that is optimal (near the word's middle), there will be a single fixation. However, if the eyes land in a nonoptimal position, a refixation will generally occur. Fixation durations according to this scheme are mainly determined by oculomotor constraints. The probability that a word is refixated does not depend on its lexical status, but instead on lower level visual factors such as the landing position in that word. Linguistic factors influence the duration of a single long fixation (presumably 300 ms or longer, see O'Regan, 1992), but only the second of two fixations in a refixated word.

There are some problems associated with O'Regan's approach. The optimal viewing position effect was originally obtained in tasks in which words were presented in isolation (Nazir, Heller, & Sussmann, 1992; O'Regan & Jacobs, 1992; O'Regan & Levy-Schoen, 1987; O'Regan et al., 1984). Normal reading, however, involves much more than recognizing individual words. O'Regan and colleagues have examined whether, in normal reading, the optimal viewing position effect for words is still obtained (Vitu, 1991; Vitu et al., 1990). In these studies, although the refixation effect (i.e., readers are more likely to refixate a word if the initial fixation is away from the optimal viewing position) still obtained, the processing cost effect (i.e., a cost of 20 ms per character that the fixation is away from the optimal viewing position) was greatly attenuated or absent.

O'Regan's experimental situation, in which words are presented around a central fixation mark, has raised another concern. A. B. Sereno (1992) has pointed out that the optimal viewing-position effect itself might be an artifact of these experimental procedures and could be alternatively explained as the result of attentional mechanisms. In O'Regan's task, spatial expectations about where a word will appear relative to the fixation mark are generated. Consider, for example, a subset of five 5-letter words. The words are presented at different spatial offsets relative to a central fixation mark. Each word is presented once, with the point of fixation at a different letter position for each word: One 5-letter word is presented with its first character at the fixation mark, extending four characters to the right; a second word is presented with its second letter at fixation, extending three characters to the right, and so on. Across all five trials, there is information (i.e., a letter) at fixation. However, there is information at the region "four characters to the right" on only one trial. Thus, over all trials, as the distance from the fixation mark increases, the probability that a letter will appear at more eccentric locations decreases. On the assumption that the attentional gradient of facilitation depends on task demands (see, e.g., LaBerge & Brown, 1986), less attention will be allocated to more eccentric locations. When a five-letter word is centered about the fixation mark (fixation at the third letter), optimal circumstances for attentional viewing prevail and fixation time on the word is minimized.

Testing the Models

In the present study, we examined fixation time on 5- to 10-letter low-frequency (LF) and high-frequency (HF) words as a function of eye position. The LF and HF targets were embedded in passages of text that had been read by a number of participants as part of three previous experiments in our laboratory. Fixation duration and landing position were analyzed both when only single fixations were made and when two consecutive fixations were made; in both cases, we examined only fixations that followed forward first-pass (left-to-right) saccades.

Morrison's model assumes that lexical factors largely determine when to move the eyes. Frequency effects should be found for all landing positions and possibly for all fixations. O'Regan's model, on the other hand, assumes that oculomotor factors determine when to move the eyes. The
eyes' initial landing position on a word, not the word's lexical status, should be a strong predictor of fixation duration and refixation probability. Lexical variables should influence only fixation time on single long fixations or the second fixation of refixed words. Also, although O'Regan's model does not directly address how fixation location affects single fixations, it would seem—given the importance the model places on fixation location—that for such fixations, the further from the optimal viewing position that fixations occur, the longer they should be, or frequency effects should be greatly reduced at more distant locations.

Method

Participants

A total of 61 participants from the University of Massachusetts community took part in one of three experiments performed earlier in our laboratory. They all had normal uncorrected vision.

Materials

The texts were all short narratives or descriptive texts that extended over 12 to 15 lines and consisted of about 150 words. Within the passages, LF and HF target words were identified. The LF words had frequencies of 10 per million or less, and HF words had frequencies of 50 per million or greater, as computed from the Francis and Kucera (1982) norms. Each LF word was matched in length to a HF word. In addition, there were an equal number of words that were 5, 6, 7, 8, 9, and 10 letters in length. Target words were identified in passages from each of the three experiments. From the first experiment (28 participants), 4 LF and 4 HF words at each of the six-letter lengths were identified (24 LF, 24 HF words); from the second experiment (18 participants), 8 LF and 8 HF words at each letter length were identified (48 LF, 48 HF words); and from the last experiment (15 participants), 3 LF and 3 HF words at each letter length were identified (18 LF, 18 HF words). Thus, for each word length, there were 301 possible data points for LF words and 301 for HF words.

Finally, a number of criteria were used in selecting target words. All of the targets were nouns located in the middle portion of a line of text, not sentence-final, and the first occurrence of the word in a passage, if it occurred more than once. Also, in selecting LF target words, we avoided words with unusual spelling patterns. Examples of LF target words are casks, sedan, derby, mural, sirens, harbor, grapes, barrier, cookies, panther, peasants, vineyard, ambulance, classroom, classmates, and demolition.

Apparatus

All three experiments from which the data were collected were performed on the same apparatus. The passages of text were presented on a SONY Trinitron monitor that was interfaced with an Epson Equity III computer. The letters, which were yellow on a black background, were formed from a 5 × 8 dot matrix and were presented in standard upper and lower case format. Participants were seated 80 cm from the monitor. Three characters equaled 1° of visual angle, and the vertical spacing between lines was 1.5° of visual angle. The maximum line length was 60 characters.

Participants' eye movements were monitored with a Stanford Research Institute Dual Purkinje Eyetracker, which was also interfaced to the Equity computer. The Eyetracker has a resolution of 10 min of arc (one half of a character), and the signal from the Eyetracker was sampled every millisecond by the computer. Although viewing was binocular, eye movements were recorded from the right eye.

Procedure

When participants arrived in the laboratory, they were introduced to the apparatus and a bite bar was prepared that served to stabilize the head. The initial calibration of the eyetracking system generally required about 5 to 10 min. Participants were given a few practice trials to become familiar with the procedure (see Raney & Rayner, 1995; Rayner, Garrod, & Perfetti, 1992, for details). They were told to read the text normally, and they were told that they would be asked comprehension questions after each passage. The questions consisted of true–false, yes–no, or short answer questions. Participants were able to answer these questions without difficulty.

Results and Discussion

A number of analyses were undertaken. Some of the analyses involved overall characteristics of the data set, whereas others more specifically addressed the debate over what controls eye movements in reading. Note that in scoring the data, the target region for a word included the space before the word.

Global Analyses

Tables 1, 2, and 3 provide some descriptive characteristics of the data set. Table 1 presents the means across different fixation time measures for LF and HF words as a function of word length. Table 2 presents the mean launch site and the mean landing position for LF and HF words as a function of word length. Table 3 shows fixation probability measures for LF and HF words as a function of word length. In general, these data are quite consistent with previous reports. Table 1 shows that (a) LF words were fixated longer than HF words when the measure of processing time was either a single fixation, the first or second fixation of a refixed word, or gaze duration (see Kennison & Clifton, 1995; Rayner & Duffy, 1986; Raney & Rayner, 1995; Rayner, Sereno, Morris, Schmauder, & Clifton, 1989; S. C. Sereno, 1992), (b) the amount of time spent fixating a word increased as word length increased (see Rayner & McConkie, 1976; Vitu et al., 1990), and (c) the duration of a single fixation was longer than either of the two fixations

8 A check of the Mayzner and Tresselt (1965) norms revealed no difference between the HF and LF target words in single-letter or digram frequency counts for five–seven letter words. The average single-letter position frequency count was 217 for the LF and 227 for the HF words; the average digram frequency count was 30 and 32 for the LF and HF words, respectively.

9 Gaze duration represents the sum of all consecutive fixations on a word before the eyes move to another word. It includes both single and multiple fixation cases.
of refixed words (see O'Regan, 1990; S. C. Sereno, 1992; Vitu & O'Regan, 1995; Vitu et al., 1990).

Table 2 shows that (a) the mean launch site for LF and HF words did not differ for the target words that we used and (b) the mean landing position in a word (the preferred viewing location) shifted to the right as word length increased (see Radach & Kempe, 1993; Rayner, 1979). Further examination of the launch site effect revealed results that were very consistent with results reported previously by McConkie et al. (1988). Specifically, as shown in Figure 1, the landing position distribution shifted as a function of the launch site; the distribution shifted to the left when the launch site was further from the beginning of the target word (e.g., more than seven letter spaces) and shifted to the right when the launch site was close to the beginning of the target word (e.g., 2–1 letter spaces away). Critically, the launch site effect was identical for LF and HF words.

Given that the launch sites were relatively similar across the different target word lengths and that the landing position shifted to the right as word length increased, the average saccade length into the target word increased as its length increased. The average saccade length into the target word was 8.3, 8.5, 9.0, 9.4, 9.7, and 10.1 letter spaces for 5-

<table>
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<th>Fixation time measure</th>
<th>Word length (no. of letters)</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
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<td>HF</td>
<td>229</td>
<td>229</td>
<td>249</td>
<td>250</td>
<td>253</td>
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<td>226</td>
<td>238</td>
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<td>214</td>
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<td>196</td>
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<td>277</td>
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<td>310</td>
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Table 2 Mean Launch Site and Mean Launching Position for Low-Frequency (LF) and High-Frequency (HF) Words as a Function of Word Length

<table>
<thead>
<tr>
<th>Measure</th>
<th>Word length (no. of letters)</th>
<th>5</th>
<th>6</th>
<th>7</th>
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<td>5.2</td>
<td>5.3</td>
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<td></td>
<td>HF</td>
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<td>5.4</td>
<td>5.3</td>
<td>5.4</td>
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<td>Mean landing position</td>
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<td>3.7</td>
<td>4.1</td>
<td>4.4</td>
<td>4.7</td>
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<tr>
<td></td>
<td>HF</td>
<td>2.7</td>
<td>3.2</td>
<td>3.6</td>
<td>4.1</td>
<td>4.4</td>
<td>4.5</td>
</tr>
</tbody>
</table>

*In character spaces from the beginning of the target word. *In character spaces.

through 10-letter target words, respectively. This result is consistent with prior reports that saccade length increased as the length of the word to the right of fixation increased (Blanchard et al., 1989; Rayner, 1979). Critically, there were no differences in average saccade length into LF and HF target words.

Table 3 shows that (a) long words were more likely to be refixed than shorter words (see Rayner & McConkie, 1976) and (b) there was a tendency for five- and six-letter HF words to be skipped more often than LF words. With respect to this latter tendency, we examined skipping rates as a function of launch site. As can be seen in Figure 2, five- and six-letter HF target words were skipped more frequently than LF words with shorter launch site distances; there were reliable differences when the launch site was either 4–3 or 2–1 letter spaces from the beginning of the target word for both the five- and six-letter words, ts(60) > 2.7, ps < .01, whereas there were no differences when the launch site was 6–5, 8–7, 10–9, or more than 11 letter spaces away. O'Regan, Vitu, Radach, and Kerr (1994) recently discussed data from two studies that examined skipping rates for HF and LF words as a function of launch site; in one data set there were no difference between HF and LF words for launch sites between 1 and 11 letter spaces, whereas there were consistent differences in the other data set. Our data suggest that the length of the target word and the launch site distance are both important.

There are two other conclusions from the overall data set. First, in refixed words, the duration of the second fixation was shorter than the first (Table 1). This is in contrast to findings from studies that examined words in isolation (see O'Regan & Levy-Schoen, 1987) or words near the beginning of sentences (S. C. Sereno, 1992). Second, most of the target words were read with a single fixation (Table 3). This result might be somewhat problematic for the oculomotor model because of its emphasis on differences (and tradeoffs) between the first and second fixations in refixed words.

Finally, we examined the probability of refixating a word (prior to moving to another word) as a function of the initial landing position on the word. Figure 3 shows these data.
Consistent with prior reports (O'Regan, 1992; Vitu & O'Regan, 1995; Vitu et al., 1990), participants were much more likely to re-fixate a word if they initially landed on the beginning or end of the word than if they landed near its middle. By far, the most frequent pattern was for readers to fixate the beginning of a word and then fixate at the end (38% of the two fixation cases). The next most frequent pattern was to fixate the beginning and then the middle of the word (19%). The frequency of other patterns was as follows: initial fixation in the middle followed by a fixation at the end (14%), initial fixation in the middle followed by a fixation at the beginning (11%), initial fixation at the end followed by a fixation in the middle (11%), and, finally, initial fixation at the end followed by a fixation at the beginning (7%).

With respect to these different patterns, we examined the duration of fixations when readers initially fixated at the beginning of the word, the middle of the word, or the end of the word. This analysis was undertaken on five- and eight-letter words because it was easier to unambiguously categorize a fixation as being at the beginning, middle, or end of the word (including the space before the word, there were 2 or 3 characters per region, respectively). We examined the duration of the first and second fixation as a function of the location of the first fixation (for the purpose of this analysis, the location of the second fixation was irrelevant). A subset of 33 participants who consistently made two fixations on words was used for the analysis. This analysis revealed that the duration of the initial fixation did not vary as a function of where the fixation was located (221, 219, and 222 ms for the beginning, middle, and end, respectively). The duration of the second fixation, however, did vary as a function of the location of the first: When the first fixation was located at the beginning of the word, the duration of the second
Probability of skipping five-letter (left) and six-letter (right) low-frequency and high-frequency words as a function of launch site (2–1, 4–3, 6–5, 8–7, 10–9, or more than 11 letter spaces to the left of the target word).

Fixation was 225 ms; when the first was at the middle, the second fixation was 182 ms; and when the first was at the end, the second was 197 ms. One possible explanation for this finding is that less processing of the word can be done when the initial fixation is at a word's beginning, which leaves more processing to be done during the second fixation. An analysis of variance (ANOVA) on these data revealed a main effect of first versus second fixation, $F(1, 32) = 10.74, p < .01$; a main effect of initial fixation location, $F(2, 64) = 15.05, p < .001$; and an interaction of the two, $F(2, 64) = 10.7, p < .001$. Pairwise comparisons on the second fixation data revealed that, when the first fixation was at the beginning of the word, the duration of the second fixation was significantly longer ($ps < .05$) than the second fixation in the other two conditions (which did not differ from each other).

Refixation probability as a function of the initial landing position in words 5 to 10 letters long. (Note that each word length is represented by a separate plot that is centered around the midpoint of the horizontal axis.)
Testing the Oculomotor Model

An oculomotor model such as O'Regan's accounts for refixation in the following way: The eyes initially land in a nonoptimal place in the word, and a within-word fixation is immediately programmed. On this view, the frequency of the refixated word should not affect the duration of the first fixation. Likewise, refixation probability itself should not depend on word frequency, but only on initial landing position. Obviously, not all words are refixated. In fact, as noted above, most words receive only a single fixation. What happens when a word is fixated only once and that fixation is not at the optimal viewing position? An oculomotor model would have to predict that, when the reader is fixated some distance from the optimal viewing position, there should be an effect of word frequency only if such fixations are notably long. We now turn to analyses designed to explore these predictions.

Word frequency effects on first fixations of refixated words. There is currently some discrepancy in the literature concerning whether word frequency effects occur on the first of two fixations on a word. O'Regan and Levy-Schoen (1987) reported that there was no frequency effect on the first fixation (with participants fixating words presented in isolation), whereas S. C. Sereno (1992) found such an effect (with participants reading sentences).

To examine this effect, two analyses were performed. In the first analysis, we collapsed across all of the participants and across all of the words of a given length and then examined the duration of first and second fixations as a function of word frequency.10 The resulting data are shown in Table 4. A 2 (frequency: LF, HF) × 2 (fixation number: first, second) ANOVA revealed highly significant main effects of frequency, $F(1, 5) = 38.37, p < .01$, and of fixation number, $F(1, 5) = 36.26, p < .01$, with no interaction. The second analysis involved the subset of 33 participants who consistently made two fixations on words. Again, we performed a $2 \times 2$ ANOVA on the data.11 This analysis also yielded significant effects of frequency, $F(1, 32) = 14.92, p < .001$, and of fixation number, $F(1, 32) = 13.11, p < .001$, with no interaction. Subsequent contrasts, as follow-ups to the two ANOVAs, specifically comparing the first fixation of LF and HF words showed a significant word frequency effect, $F(1, 5) = 28.9, p < .01$, and $F(1, 32) = 9.67, p < .01$, for all participants across landing position and for the subset of participants who refixated, respectively. Together, these analyses show that the second of two fixations is shorter than the first. More important, they confirm S. C. Sereno's (1992) report of a word frequency effect on the first of two fixations of refixated words.

Refixation probability and word frequency. If the decision to refixate words were based purely on low-level oculomotor constraints, then the refixation probability should not differ for LF and HF words, assuming that word length and initial landing position between these two types of words are roughly equal. Analyses of the data including each word length indicated that word frequency, however, did affect refixation probability (see Table 3). Specifically, a $6 \times 2$ ANOVA (using all 61 participants) revealed significant main effects of word length, $F(5, 300) = 29.54, p < .001$, and word frequency, $F(1, 60) = 13.06, p < .001$, with no interaction of the two variables, $F < 1$. Given that the launch site and landing position for LF and HF words was comparable for all word lengths (see Table 2), this result clearly demonstrates that readers are more likely to refixate LF than HF words.

Single fixation word frequency effects and landing position. If oculomotor factors, specifically where the eyes happen to land in a word, have more influence on fixation times than do lexical variables (such as word frequency), then, when the eyes land at positions somewhat deviant from the optimal viewing location, either (a) fixations should be particularly long and show frequency effects or (b) there should not be a word frequency effect. To test this prediction, we examined fixation durations in cases in which readers made a single fixation on LF and HF words varying in length from 5 to 10 letters. In this analysis, we collapsed across participants and used the different length target words as the unit of analysis (15 LF and 15 HF words at each word length). This procedure may be somewhat problematic because it includes variability that exists because of individual differences in fixation time (see Rayner, 1978). On the other hand, it resulted in considerably fewer missing data points than when participants were used as the unit of analysis.12 When this analysis was done collapsing across words, there were many missing data points because many participants often did not fixate on the ends of words. Despite the large number of missing data points, analyses using participants as the unit of analysis yielded effects that were generally similar to those performed on items.

Figure 4 shows the percentage of fixations and their duration at each landing position for 5- to 7-letter LF and HF words. We have presented data only for 5- to 7-letter words because there was a reasonable number of data points for fixations at the ends of these words. For 8- to 10-letter words, there was considerably more variability in fixation

<table>
<thead>
<tr>
<th>Measure</th>
<th>LF</th>
<th>HF</th>
</tr>
</thead>
<tbody>
<tr>
<td>First fixation</td>
<td>238</td>
<td>215</td>
</tr>
<tr>
<td>Second fixation</td>
<td>211</td>
<td>175</td>
</tr>
</tbody>
</table>

Table 4
Mean Fixation Time (in Milliseconds) for Low-Frequency (LF) and High-Frequency (HF) Words for First and Second Fixations on the Target

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10 In this analysis, word length would be equivalent to subjects in a subjects-as-random effect analysis or to items in an items-as-random effect analysis.
11 Words of various lengths were fairly equally represented across participants.
12 In cases in which there were missing data points, the missing value was replaced by the mean for that condition. Obviously, missing data points were more likely for fixations on the ends of words. The number of raw data points for the fixation durations shown in Figure 4 range from 14 (for the 7th letter position for HF 7-letter words) to well over 50 (when the eyes landed on the preferred viewing location).
times, particularly for letters at the ends, presumably because there were fewer data points (although, as documented below, frequency effects were evident). As before, fixations on the space preceding the word were included as part of the word region (Position 0 in Figure 4).

As is apparent in Figure 4, the eyes tended to land more frequently near the middle of the words. This is consistent with previous reports (McConkie et al., 1988, 1989; Radach & Kempe, 1993; Rayner, 1979; Vitu et al., 1995). It is also apparent that fixation durations were not long (i.e., more than 300 ms).

ANOVAs (Frequency × Landing Position) were performed on the fixation duration data for each word length. These analyses revealed main effects of word frequency, but no main effects of landing position and no interaction between the two variables. The $F$ values (all with 1 and 28 dfs) and significance levels of the frequency effect for the different word lengths were as follows: 5 letters = 26.88, $p < .001$; 6 letters = 27.44, $p < .001$; 7 letters = 15.88, $p < .001$; 8 letters = 5.88, $p < .05$; 9 letters = 4.74, $p < .05$; and 10 letters = 4.55, $p < .05$. The $F$ values for the effect of landing position and the interaction were generally either less than one or close to one. Importantly, these analyses show that there was no increase in fixation time as the distance from the optimal viewing position increased.

**General Discussion**

In the data reported in this article, word frequency effects were present in single fixations, in both the first and second fixation of refixed words, and in the gaze duration measure. If low-level oculomotor factors are crucial in directing eye movements, the following predictions should be upheld: (a) Word frequency effects should not be evident in the first fixation of refixed words; (b) the probability of refixating a word should not depend on its word frequency; and (c) when the only fixation on a word is at a position somewhat deviant from the optimal viewing position, fixation times should be longer or word frequency effects attenuated. None of these predictions, however, were supported by the data reported here. First, the present data and S. C. Sereno's (1992) data both showed frequency effects on the first fixation of refixed words. Second, refixation probability did depend on word frequency. Vitu (1991) showed similar results in a study using words in sentences, and O'Regan (1992) acknowledged that this finding was problematic for his model. Finally, the frequency effect in single fixations was independent of the landing position on the target word and fixation times did not vary as a function of landing position. These findings, together, indicate that in a normal reading situation—one in which parafoveal previews are available and words exist in the context of a connected discourse—readers are quite flexible in the amount of information that can be processed on any given fixation. That is, being fixated at the optimal viewing position may not be as important when identifying words in reading as it is in identifying words in isolation.

Another problem for the oculomotor model, which is apparent from the data reported here, is that most of the time readers made only a single fixation on target words ranging in length from 5 to 10 letters. Even 9- and 10-letter low-frequency words received a single fixation more than 70% of the time. These words in isolation would be refixated considerably more often than 25–30% of the time (see O'Regan, 1992). However, given that the goal is to understand eye movement control during reading and given that most words are read with single fixations, it would seem most appropriate to focus on eye movements between rather than within words. Of course, explaining refixations on words is important for any model of eye movement control in reading (Pollatsek & Rayner, 1990). Our point is simply that reading is quite complex and attempting to generalize from eye movement behavior when single words are read to eye movement control in reading may be somewhat hazardous, as the present results document.

Although some of our data present problems for the oculomotor model, other aspects of the data are consistent with such a model. In particular, we found that the proba-
bility of refixating a word was strongly influenced by the initial landing position. When the eyes initially landed at the beginning or end of a word, readers were more likely to refixate it than when they initially fixated nearer to the middle of the word. However, note that there were a significant number of refixations on words when the eyes initially landed in the middle of the word. Refixations on words therefore are likely due to two factors: (a) initially landing at a point in the word at which maximal information cannot be obtained, and (b) difficulty with accessing the appropriate meaning of the word (see Pollatsek & Rayner, 1990; Rayner & Pollatsek, 1987).

One final aspect of our data with respect to other data is relevant. Recently, proponents of the oculomotor model (see O'Regan et al., 1994; Vitu & O'Regan, 1995) have examined the durations of single fixations on LF and HF words. They presented graphs showing fixation durations as a function of landing position (similar to our Figure 4) and argued that single fixations falling near the middle of words are longer than those falling near the beginning or end of words. This is an interesting finding because it is not easily accounted for by either type of model. However, of the two sets of data discussed by O'Regan et al. (1994), one of the sets (collected by Radach) shows a fairly flat function of fixation duration across landing position, much as we reported. The important finding, for our purposes, is that there were fixation duration differences between LF and HF words independent of the landing position.

Finally, the data reported here seem consistent with a moment-to-moment or local processing type of model. However, it is important to note that oculomotor models (such as O'Regan's model) make testable predictions with respect to how fixation location should affect fixation duration. Also, some of the data reported in this article (effects of launch site on landing position, refixation probability as a function of landing position) are, as we have noted, quite consistent both with prior research (McConkie et al., 1988, 1989; O'Regan & Vitu, 1995; Vitu et al., 1990, 1994, 1995) and with predictions from the oculomotor type of model. Although local processing models (such as Morrison's, 1984, model) make explicit testable predictions concerning other aspects of eye movement control, they do not address the extent to which landing position affects fixation time or specify mechanisms involved in refixations (see Pollatsek & Rayner, 1990, for a discussion of this issue).13 Perhaps some type of hybrid model that combines features of both models could best account for eye movement control. Finally, a problem with the models may be that neither model is sufficiently precise for comprehensive testing. Future instantiations of models of eye movement control in reading must be made more explicit, perhaps through the use of mathematical or computational modeling.

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13 It is curious in this regard that O'Regan et al. (1994) recently suggested that local processing models (such as Morrison's) predict that when single fixations are made on a word and the fixation is either at the beginning or the end of the word, fixations should be longer than when the initial fixation is in the middle of the word. To our knowledge, advocates of local processing models have made no such claims, nor would the suggestion necessarily seem to follow logically from the models. Also, although it may be that lexical access or some other local process would take longer the further the reader was from the center of the word, it is not clear what the size of such an effect would be.
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