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Mindless reading revisited: Eye movements during reading and scanning are different

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In an extension of a study by Vitu, O'Regan, Inhoff, and Topolski (1995), we compared global and local characteristics of eye movements during (1) reading, (2) the scanning of transformed text (in which each letter was replaced with a *z*), and (3) visual search. Additionally, we examined eye behavior with respect to specific target words of high or low frequency. Globally, the reading condition led to shorter fixations, longer saccades, and less frequent skipping of target strings than did scanning transformed text. Locally, the manipulation of word frequency affected fixation durations on the target word during reading, but not during visual search or *z*-string scanning. There were also more refixations on target words in reading than in scanning. Contrary to Vitu et al.'s (1995) findings, our results show that eye movements are not guided by a global strategy and local tactics, but by immediate processing demands.

During the past few years there has been a debate regarding the type of model that can most adequately account for eye movement behavior during reading (see Rayner, Sereno, & Raney, in press, and Vitu, O'Regan, Inhoff, & Topolski, 1995, for two recent examples of this debate). Any serious account of such eye movement behavior must explain *where* the reader fixates next and *when* the reader moves his/her eyes. Vitu et al. (1995) have referred to the two main types of models that have addressed this issue as *processing* models and *oculomotor* models. One characteristic that distinguishes between these two types of models is whether they conceptualize the two decisions regarding the spatial aspects (the *where* decision) and the temporal aspects (the *when* decision) of eye behavior during reading as independent.

According to the processing models (Henderson & Ferreira, 1990; Morrison, 1984; Rayner & McConkie, 1976; Rayner & Pollatsek, 1989; Rayner et al., in press), the *when* decision is primarily affected by linguistic variables so that fixation times on words reflect moment-to-moment processing complexities of the language. For example, the frequency of a currently fixated word affects how easy the word is to identify, and thus determines the time the eyes spend on the word. Somewhat independently from this, the *where* decision is affected by perceptual aspects of the forthcoming word, such as its length and distance from the current fixation, reflecting the reader's attempt to maximize letter identification (see, e.g., McConkie, Kerr, Reddix, & Zola, 1988). Spatial eye behavior (the where decision) is, however, not directly affected by lexical factors such as the information distribution in the forthcoming word (e.g., Rayner & Morris, 1992). It may indirectly be affected by the ease of processing of a parafoveal word, as will be described below. In summary, processing models focus primarily on the temporal aspect of eye behavior, but the spatial aspect of this behavior is also important.

Oculomotor models (O'Regan, 1990, 1992), on the other hand, focus primarily on the spatial aspect of eye behavior. Thus, the location in a word at which the eyes are initially fixated largely determines how long the eyes remain fixated. Perceptual considerations, such as the strong loss of visual resolution from foveal to parafoveal vision, have led oculomotor theorists to tightly link the ease of processing of a word to the location at which the word is being fixated. In this sense, the *when* decision depends on the outcome of the previous *where* decision. A detailed algorithm of this sort will be described below.

Proponents of both types of models can point to various results in support of the model they advocate. Consistent with the processing model's focus on temporal aspects of eye behavior, the gaze duration (i.e., the time the eyes spend on a word prior to moving to another word) and the durations of individual fixations are strongly influenced by word frequency (Inhoff, 1984; Inhoff & Rayner, 1986; Rayner & Duffy, 1986; Rayner, Sereno, Morris, Schmauder, & Clifton, 1989; Rayner et al., in press) and by the predictability of a word from prior context (Balota, Pollatsek, & Rayner, 1985; Ehrlich & Rayner, 1981; Zola, 1984). Word frequency and predictability are also known to affect the probability of refixating a word (i.e., the probability of making another fixation on a word before moving to a new word). In addition, a number of other linguistic variables have been shown to influence eye fixations (for reviews, see Rayner et al.,

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1989; Rayner & Pollatsek, 1987, 1989; Rayner & Sereno, 1994).

Other observations regarding the spatial aspect of eye movements in reading lend support to oculomotor models of eye movement control during reading. For example, it has been shown that the position that the eyes land in a word does not depend on the linguistic context (O'Regan, 1990; Rayner & Morris, 1992) or on the availability of the word in parafoveal vision (Inhoff, 1989; Vitu, 1991), but rather, on the lengths of the fixated word and surrounding words (O'Regan, 1979; Rayner, 1979; Vitu, 1991). The landing site of the eyes in a word is also influenced by where the eyes came from on the prior fixation (McConkie et al., 1988; Radach & Kempe, 1993; Rayner et al., in press). Likewise, within-word eye behavior can be influenced by low-level oculomotor factors (Vitu, 1993).

Clearly, both approaches to understanding eye movements in reading have their merits. To discriminate between the two types of models, it is useful to consider in more detail a prototypical model of each type. Thus, we will describe the processing model proposed by Morrison (1984) and the oculomotor model proposed by O'Regan (1990, 1992).

According to Morrison's (1984) model, at the beginning of each eye fixation, attention is oriented on the foveal word (word *n*). After foveal word processing has reached some criterial level (such as lexical access), attention shifts to a parafoveal word (word $n+1$) during the fixation. The 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 move to the new word. Because there is a lag between the attentional shift and the actual eye movement (due to motor programming latency), information accumulates from the parafoveal word before it is directly fixated. If the parafoveal word is identified quickly, attention can thus shift to the next parafoveal word (word $n+2$) before the eye movement to word $n+1$ is fully programmed. In this case, the motor program that would have directed the eyes to word $n+1$ is modified and the eyes move to word $n+2$, skipping word $n+1$. However, there is a cost in modifying the motor program, and this is reflected in an inflated duration of the fixation prior to a skip (Hogaboam, 1983; Pollatsek, Rayner, & Balota, 1986). If the motor program to direct the eyes to word $n+1$ is too far advanced for its modification, however, the two programs will both be executed in rapid sequence, or they will be merged. Consequently, there will either be (1) a short fixation on word $n+1$ followed by a longer fixation on word $n+2$, or (2) a fixation located at an intermediate position between words $n+1$ and $n+2$. Via the attentional mechanisms just described, Morrison's model accounts for two puzzling aspects of eye movement behavior in reading: (1) very short fixations (e.g., under 100 msec) given that saccade latency in simple oculomotor tasks is typically on the order of 175–200 msec (Rayner, Slowiaczek, Clifton, & Bertera, 1983; Salthouse & Ellis, 1980); and (2) unusual fixation locations (e.g., the spaces between words).

A major problem with Morrison's (1984) original model is that there was no explanation for why words are sometimes refixated: If lexical access is the trigger for attentional shifts and eye movements, the reader should never refixate on the currently fixated word before moving to the next word. A modification of Morrison's model by Henderson and Ferreira (1990; see also Sereno, 1992) suggested 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, resulting in a refixation on the word. In another modification of the original model, Pollatsek and Rayner (1990) suggested that the signal to stay on a word may be related to the decision that something does not fully compute. For example, the word that has been accessed might not fit into the syntactic or semantic structure of the sentence being constructed.

According to O'Regan's (1990, 1992) strategy–tactics model, the eyes' initial landing position in a word primarily determines how long they remain fixated and where the following fixation is made. O'Regan argued that readers adopt a global strategy of either careful or risky reading that coarsely influences fixation times and saccade lengths. He further argued that readers implement local within-word tactics that are based on lower level, nonlexical information available early during the first fixation on a word, such as the distance of the current fixation from the spaces surrounding the currently fixated word. The question is whether there is any convincing evidence in favor of the proposed global strategy and the local tactics of eye movement control during reading. We will first discuss the operation and control of the within-word tactics because they are most relevant to the current debate.

The tactics module of O'Regan's (1990, 1992) model operates on the basis of an evaluation of the current eye position of the initial fixation in a new word. If the eyes land at a region in a word that is perceptually optimal for the processing of its constituent letters (i.e., near the middle of the word), then the word will be fixated only once and will be lexically processed during this fixation if the fixation is relatively long (i.e., over 300 msec). However, if the eyes land at a nonoptimal location, a refixation elsewhere in the same word is quickly initiated without regard for the lexical status of this word. In this situation, effects of lexical processing can thus only be reflected in the second of two fixations in the same word. In summary, the strategy–tactics model proposes that fixation durations are determined mainly by oculomotor constraints, and that the probability that a word will be refixated does not depend on its lexical status, but on the initial landing position of the eyes within that word. Furthermore, according to the model, linguistic factors, such as word frequency, influence only long single fixations or the second of two fixations in a refixated word.

One problem with this hypothesis is that it was originally based on research in which words were presented in isolation, whereas normal reading involves more than recognizing individual words. In agreement with the model's assumption, reading studies have demonstrated that readers are more likely to refixate a word if they initially fixate away from the optimal viewing location (Rayner et al., in press; Vitu, 1991; Vitu, O'Regan, & Mittau, 1990). However, fixation durations in reading are not strictly determined by the initial landing position in a word (Vitu et al., 1990). For example, Rayner et al. (in press) found systematic effects of word frequency on the duration of both the first and the second of two fixations in a word (see also Rayner et al., 1989; Sereno, 1992). Furthermore, we believe that the strategy–tactics theory overemphasizes the role of refixations in reading. Single fixations occur much more often than do refixations, yet the durations of these single fixations are typically below 300 msec. Finally, fixation durations on high- and low-frequency words in Rayner et al. (in press) were independent of the landing position in the word when only a single fixation was made, thus exhibiting no fixation cost as a consequence of being fixated at a suboptimal viewing position in the word. In summary, there is now growing evidence against the existence of the proposed oculomotor tactic in reading.

We now turn to a discussion of the global, strategic component of the strategy–tactics model. Vitu et al. (1995) recently provided a first direct test of this hypothesis and claimed to have found evidence to support it. In their study, subjects read normal text or scanned lines in which all of the letters from the original text were replaced with *z*s. They found that eye movement characteristics were quite similar when subjects read text or scanned *z*-strings under instructions to pretend that they were reading. Vitu et al. argued that both global characteristics (e.g., the length of saccades, durations of fixations, and the frequency distribution of fixation durations and saccade lengths) and local characteristics (e.g., skipping rates, landing position, and refixation probability) of eye movements were quite similar. From this, they argued that "the astonishing resemblance observed between the global and local characteristics of eye movements, during normal-text reading and during the scanning of meaningless letter strings, suggests that predetermined oculomotor strategies might be an important element in determining oculomotor behavior during normal-text reading, influencing which word to go to next, where to land in a word, and how many fixations to make on any particular word" (Vitu et al., 1995, pp. 361–362).

The Present Study

The present study was concerned with whether eye behavior during reading and scanning is similar, and whether such a finding, if it were true, would be remarkable. We provide evidence that eye movement data obtained during scanning might mimic reading superficially, but that they differ from reading behavior in some fundamental ways.

Like Vitu et al. (1995), we examined the eye movement characteristics of subjects who read normal sentences and scanned *z*-transformed versions of these sentences. However, we added three important experimental manipulations to our study. First, we addressed the question of whether there is a global setting of eye movement parameters depending on the reader's expectations about the processing difficulty of the forthcoming sentences. To investigate this issue, we presented normal and *z*-transformed sentences either in a blocked or in a randomized sequence. This provided a more clear-cut manipulation of the strategic adjustment of eye movements than did Vitu et al.'s (1995) frequent alternation between normal and transformed text. According to O'Regan's (1990, 1992) strategy–tactics hypothesis, the blocked presentation should allow for a strategic adjustment of global eye movement parameters, whereas in the randomized presentation order, subjects can adjust their eye movement behavior only on the basis of the visual information they process during each trial. Thus, any differences between reading and scanning eye movements due to such a general strategic adjustment should become evident from the comparison of data obtained in the blocked conditions. The same contrast between data obtained in the randomized condition should, however, not yield such a difference.

Second, unlike Vitu et al. (1995), we examined data from specific target words that were determined in advance. To this end, we prepared sentence frames in which either a high- or a low-frequency word (neither of which was predictable from the prior context) could be inserted. Thus, the visual and linguistic environment was exactly the same except for the target word. The same sentences were also converted into *z*-strings. In this condition we preserved the visual context in terms of the string lengths around each target string but excluded all possible effects of lexical processing on eye behavior. In contrast to Vitu et al.'s approach, this method allows us to evaluate whether and how eye movement behavior depends on visual or lexical context.

Third, we included a visual search condition that was somewhat different from that used by Vitu et al. (1995). In addition to the normal reading and the *z*-string conditions, Vitu et al. included two other conditions in their study: (1) a condition in which subjects searched normal text and responded each time they saw the letter *c*, and (2) a condition in which subjects searched through *z*-strings and responded each time they saw the letter *c*. In the visual search condition included in our experiment, we were also interested in examining eye behavior in a situation in which lexical information is available to the subject but is not necessarily processed. Thus, rather than reading the sentences, subjects in our visual search condition were instructed to search for a target word. The same sentences that were used in the reading condition were used in the search task; thus, either a high- or a low-frequency word was present in the sentence. Our primary motivation for including this condition was to compare it to the normal reading and *z*-string scanning conditions; it allowed us to compare eye movement measures on target words when lexical processing of each word was necessary (reading) and when it was not (search).

In terms of the comparison between normal reading and *z*-string scanning, the experimental question was how the data would compare on (1) fixation times and (2) other eye movement measures (such as the probability of skipping a word) when subjects read normal text or scanned *z*-strings. On the basis of prior data (see, e.g., Inhoff & Rayner, 1986; Raney & Rayner, 1995; Rayner & Duffy, 1986; Rayner et al., in press), we anticipated that there would be differences between the high- and low-frequency words in terms of various eye movement characteristics. We also anticipated that the visual search condition would be more like the *z*-string scanning condition than like normal reading.

METHOD

Subjects

Forty psychology students at the University of Massachusetts participated for either course credit or $5. All of the subjects had normal or corrected vision, were native speakers of English, rated themselves as fluent readers, and were naive concerning the purpose of the experiment. Thirty subjects read normal and *z*-transformed sentences, with 10 subjects each assigned to (1) blocked, normal-transformed order; (2) blocked, transformed-normal order; and (3) randomized order. The other 10 subjects searched for the target word *zebra*.

Materials

Eighty sentence frames and 160 target words were used in the normal reading condition. Sentences were selected on the basis of low predictability of the target word. In a pilot study, 10 subjects from the same population, who did not take part in the later eye movement study, were asked to predict the next word after reading each sentence up to, but not including, the target word. Only sentences in which the predictability of the target word was $p = .2$ or less were used in the subsequent eye movement experiment. Sentences had a maximal length of 70 characters and thus fit on a single line of the display.

Eighty high-frequency (HF) and 80 low-frequency (LF) nouns were selected from the Francis and Kučera (1982) norms as target words. The target words were 5, 6, 7, 8, or 9 letters long and were equally divided in terms of length. For each HF noun there was a matching LF noun of equal length that could be inserted in a given sentence frame without rendering the sentence awkward. The average frequency of occurrence in the printed language of the HF targets was 187 per million (range = 54–827), whereas the average frequency of LF targets was 3 per million (range = 1–10). Table 1 shows example sentences for each length of target word. Consistent with Vitu et al. (1995) and with Inhoff, Topolski, Vitu, and O'Regan (1993), we generated the *z*-transformed sentences by replacing all letters of the alphabet with the letter *z*, preserving letter cases, interword spaces, commas, and punctuation.

In the visual search condition, 40 filler sentences, each of which contained the search target word *zebra*, were added to the 80 target sentences. This word appeared about equally often in the first third, middle third, or end third of a sentence, and each sentence was grammatically and semantically legal or viable. Subjects were instructed to push a response key each time they encountered the word *zebra*. However, the data that were of primary interest were those from sentences in which *zebra* did not occur (so that we could examine differences between the HF and LF target words).

Table 1
Examples of Stimulus Sentences

1. He invested his money to build a *store/wharf* and was soon bankrupt.
2. Sheri and her *friend/fiance* went to Hawaii for their vacation.
3. The exhausted *student/steward* left the train and went to the station.
4. The enormous size of the *business/dinosaur* left them all dazzled.
5. The mafia boss tried to hide his *influence/deformity* from the community.

Note—High-frequency words are shown before low-frequency words.

Apparatus

A Fourward Technologies Dual Purkinje Eyetracker was used to record subjects' eye movements in the study. Viewing was binocular, but only the right eye was monitored. The eyetracker has a resolution of 10 min of arc and was interfaced with an Epson Equity III computer that controlled all aspects of the experiment and sampled the eye position every millisecond. The initiation of a fixation was defined as the point when five consecutive samples each differed from the sample taken 5 msec earlier by less than ⅓ of a character space. The initiation of a saccade was defined as the point when five consecutive samples each differed from the sample taken 5 msec earlier by more than ⅙ of a character space.

The sentences were presented on a ViewSonic 17G monitor with standard VGA characters. The characters were white on a black background and presented in upper- and lowercase format. The HF and LF target words were always located in the middle of a sentence and thus appeared near the center of the monitor. At the viewing distance used in the study (80 cm), three character spaces equaled 1° of visual angle. Since the sentences were between 56 and 70 letters in length, the total visual angle was between 18.6° and 23.3°. The brightness of the monitor was adjusted to a comfortable level for each participant and held constant throughout the study.

Procedure

Each subject was tested individually. When subjects arrived in the laboratory, a bite bar was prepared that served to eliminate head movements. Subjects were then given instructions for the experiment and a description of the apparatus, followed by an initial calibration of the eyetracker (which took about 3 min).

Prior to the presentation of each sentence, five horizontal calibration boxes were displayed where the sentence would be shown. Each box was square-shaped with a side length of ⅓ of a degree. The subject was instructed to look at each box, ending at the left-most box, which was in the same location as the first letter of the sentence would be. If the calibration was satisfactory, so that a dot that moved with the eyes fell within each calibration box, the experimenter then presented the sentence. If the calibration was unsatisfactory, the experimenter recalibrated the eyetracking system. After reading the sentence, scanning the *z*-strings, or searching for the word *zebra*, the subject pressed a response key that cleared the monitor screen. In the normal reading condition, about 20% of the normal sentences were followed by questions about their content, which the subject answered with a *yes/no* response; subjects answered these questions correctly over 90% of the time. In the visual search condition, subjects pushed different response keys to indicate whether or not the search target word *zebra* was present in the sentence. Subjects were fairly accurate in their search behavior; they missed the word *zebra* less than 8% of the time and they made false alarms less than 1% of the time.

Design

Subjects were assigned to one of four groups. Three of these groups were determined according to the order of presentation of the normal sentences and their *z*-transformed counterparts. Ten subjects first read a block of 80 normal sentences and then

Table 2
Different Eye Behavior Patterns for the Target Strings

	Target		
	z-strings	LF	HF
Total trials	2,400	1,200	1,200
Eliminated*	20.3%	9.6%	12.2%
One fixation	68.0%	70.9%	79.2%
Two fixations	25.7%	25.1%	18.4%
More fixations	6.3%	4.0%	2.4%

Note—LF, low frequency; HF, high frequency. *Elimination was due to track loss or to skipping of the target word, as well as extremely short (<500 msec) or long (>10 sec) reading times per sentence.

scanned a block of 80 lines of *z*-transformed sentences. Ten other subjects began with the block of *z*-transformed lines. Ten other subjects were presented with both types of sentences in a randomized order. All of these subjects were instructed to read the normal text for comprehension and were aware of the possibility of being questioned. Consistent with Vitu et al. (1995), the only instruction given to the subjects in the transformed text condition was that they should pretend that they were reading each line of *z*-strings. Finally, 10 subjects were asked to search through 120 sentences for the word *zebra* and to push a response key each time they saw this word. Eighty of the sentences they saw were the same ones that the other 30 subjects had seen (with the HF and LF words appropriately present and counterbalanced), while the remaining 40 sentences contained the word *zebra*.

Each subject in the reading and *z*-string conditions saw each sentence twice, once as normal text and once as *z*-transformed text. The subjects thus saw either only the HF or only the LF target word, but not both. However, since the *z*-transformed strings cannot be distinguished by word frequency, there were twice as many observations for each target word length in the *z*-transformed condition as for the HF and LF target words.

Data Analysis

Trials were eliminated after a track loss of the eyetracker during data collection (due to eye blinks), or when subjects either responded prematurely (i.e., finished reading or searching the sentence after less than 500 msec of stimulus exposure) or forgot to respond (i.e., finished reading or searching the sentence after 10 sec). Table 2 shows the percentage of eliminated data in each of the three text conditions when subjects read either normal text or *z*-strings; these data will be discussed separately from the visual search data. Consistent with many prior studies, including Vitu et al. (1995), only fixations lasting more than 50 msec were analyzed. Track losses resulted on 7.4% of the trials. Two sets of analyses were performed on the remaining data. Global analyses were carried out on all observations from all sentences (see below). In addition, local analyses of fixation times, skipping rates, initial landing sites, and refixation probabilities focused on observations pertaining to the target word in each line (i.e., the HF or LF words, or the corresponding strings of *zs*). A target word was considered to be fixated when the point of fixation fell either on one of its component letters or on the immediately preceding blank space. A target word was considered as having been skipped when the last fixation before it during the first-pass reading was followed by a forward saccade that brought the eyes beyond the last letter of that word. Consistent with Vitu et al. (1995), unless otherwise specified, in the local analyses means or proportions were calculated for each subject for each dependent variable, and these were averaged across subjects. Thus, the weights of individual subjects' contributions to the values were not influenced by the number of fixations in a particular cell.

RESULTS AND DISCUSSION

We will first discuss the data from the reading and *z*-string reading conditions and then discuss the visual search data. Following Vitu et al. (1995), the results are presented first on a global level, and then more local analyses are presented. The global results stem from analyses of (1) the total reading time, (2) the average fixation duration, (3) the average saccade length, and (4) frequency distributions of fixation durations and saccade lengths. These results address the issue of whether the eyes are guided by a global oculomotor strategy.

Global Analyses

We manipulated the order of presentation of normal and transformed text to investigate possible strategic adjustments of the reader's eye behavior depending on the sequence of presentation and the stimulus material. On the basis of the strategic component of O'Regan's (1990, 1992) oculomotor model of eye movement control, we expected to find strong effects of such an adjustment between the two blocked presentation conditions and no such effect within the random presentation order. These predictions were tested with a 3 (order of presentation: normal–transformed, transformed–normal, or random, varied between subjects) × 2 (text material: normal vs. *z*-transformed text, varied within subjects) mixed-factors analysis of variance (ANOVA). Separate ANOVAs were conducted on average sentence reading times, average fixation durations, and average saccade lengths.

Reading times. The average sentence reading time was strongly affected by the nature of the text material [$F(1,27) = 12.39, p < .01$]. Consistent with results reported by Vitu et al. (1995), subjects took longer to "read" a line of *z*-transformed text (4,460 msec) than to read a line of normal text (3,863 msec). Neither the effect of order of presentation [$F(2,27) = 1.83, p > .15$] nor the interaction between order and material ($F < 1$) was significant. Post hoc simple effects tests revealed that the difference between the normal text and the *z*-transformed text in the random presentation order (380 msec) was not reliable [$F(1,27) = 1.68, p > .2$]. Reading times were, on the other hand, reliably slower (by 815 msec) with *z*-transformed text that was read before the normal text condition [$F(1,27) = 7.70, p < .01$] and marginally slower (by 596 msec) when *z*-transformed text was read after normal text [$F(1,27) = 4.11, p < .06$].

Fixation duration. Eye fixation times contribute about 90% to the reading times. Therefore, the results from an analysis of fixation durations resembled those of the reading times. Consistent with Vitu et al. (1995), fixations were much longer on *z*-transformed strings (317 msec) than on normal words (279 msec) [$F(1,27) = 33.45, p < .001$]. As before, neither the effect of presentation order [$F(2,27) = 2.13, p > .10$] nor the interaction between order and material ($F < 1$) was significant. Post hoc simple effects tests revealed that the difference between fixation times in the normal text and the z-transformed text conditions was significant ($p < .01$) for all three orders of presentation. However, presentation order affected only the fixation durations with normal text [$F(2,27) = 4.13, p < .05$], where the means ranged between 258 msec in the randomized order condition, 283 msec in the condition with transformed text after normal text, and 295 msec in the condition with normal text after transformed text. The latter three values were 305, 320, and 327 msec in z-scanning; presentation order did not affect the scanning of transformed text ($F < 1$). Thus, the randomized condition led to the shortest eye fixations, and the condition that began with the z-transformed text block led to the longest eye fixations, irrespective of the text material.

Saccade length. Again consistent with Vitu et al. (1995), the mean saccade length was not influenced by the nature of the stimulus material. Forward saccade length was approximately 7 character spaces with both the normal and z-transformed text ($F < 1$). As before, neither the effect of order of presentation ($F < 1$) nor the interaction between order and material ($F < 1$) was significant.

Distributions of fixation durations and saccade lengths. Figure 1 shows the frequency distribution for fixation durations and Figure 2 shows the frequency distribution for saccade lengths in the normal text and z-transformed text conditions. Following Vitu et al. (1995), we analyzed the percentage of fixations for 10 levels (going from 125 up to 575 msec in 50-msec steps) and the percentage of saccade lengths for 9 levels (from -17.5 letters, with the negative sign indicating regressions, up to 22.5 letters in 5-letter steps). Although Vitu et al. analyzed only 10 levels of fixation duration and 9 levels of saccade length, their figures showed more data points (15 for fixation duration and 11 for saccade length). To facilitate comparisons, our figures also show more levels than those that were analyzed. A one-way comparison of the normal text condition with the z-transformed text condition was performed for each class of fixation duration and for each level of saccade length.

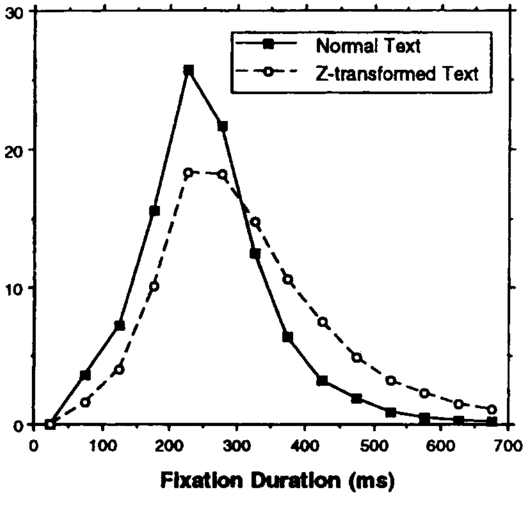

Figure 1. Distribution of all observed fixation durations during the reading of normal text (black squares) and transformed text (white circles).

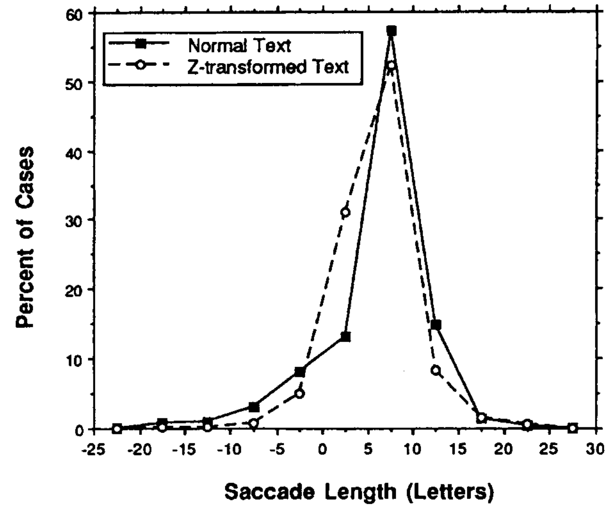

Figure 2. Distribution of all observed saccade sizes during the reading of normal text (black squares) and transformed text (white circles).

The fixation duration distribution analysis yielded a significant difference between the two text conditions for each level of fixation duration [$Fs(1,29) = 13.42$ or larger, $ps < .01$] except where the distributions crossed (the bin for fixations between 275 and 324 ms, $F < 1$). These data are quite consistent with those reported by Vitu et al. (1995).

The results of our analysis of the saccade length distribution differ from the findings of Vitu et al. (1995). While the average length of forward saccades in our study was comparable to that reported by Vitu et al. (approximately 7 characters), we found significant differences between the normal text condition and the transformed text condition for all levels of saccade length between -17.5 and 7.5 characters [$Fs(1,29) = 31.14$ or larger, $ps < .001$]. Both regressive and short progressive eye movements were generally fewer when participants looked at transformed text than when they looked at normal text. Only for the number of large forward saccades were there no reliable differences between the text conditions (all p values $> .05$; Figure 2).

Discussion of Global Analyses

In the global analyses of eye movement behavior we found that subjects had a harder time "reading" transformed text than normal text. As predicted by the oculomotor theory, the reading times reflected this difference only with the two blocked presentation orders, but not with the randomized presentation order for normal and transformed text. This result might be claimed to support the notion of a strategic adjustment of the eyes' behavior. However, a closer look at the pattern of fixation durations revealed that the randomized condition led to the shortest eye fixations, and the condition that began with the *z*-transformed text block led to the longest eye fixations for each type of material. Thus, the global eye movement adjustment depended on the presentation order of the material, rather than on the material itself. It is therefore unlikely to be in the service of the cognitive processes involved in these tasks.

This conclusion is supported by the observation that the adjustment is in the opposite direction from what the oculomotor strategy hypothesis should predict. Since no lexical information can be processed from the transformed text, fixation durations should be shorter on average than fixation durations in reading. However, both Vitu et al. (1995) and the present study showed that the eyes fixate longer on the less informative text. We therefore propose a different interpretation for any apparent similarities in the global oculomotor behavior during reading and the scanning of *z*-strings. Since we know that these tasks impose different amounts of cognitive load, the lack of effects of this manipulation on the output of the system indicates to us that visual information is processed quite differently in these two tasks. We further argue that only a processing model of eye movement control can properly capture the availability of additional (lexical) information as beneficial for the ongoing oculomotor task. Specifically, our method makes it possible to attribute the difference in fixation durations to the *lack* of lexical information, because visual information (in terms of string length) was held constant across the two text conditions.

In summary, then, the global comparison of eye movements during reading and *z*-string scanning indicates that the eyes' behavior is tuned to the central processing demands. The decision *when* to move the eyes seems to be easier when the reader can process lexical material.

Local Analyses

In this section we report analyses of eye movement behavior relative to the target string in each sentence. These analyses allow us to identify effects of visual factors (target length) and lexical factors (word frequency) on the hypothesized eye movement tactic. The results to be reported next stem from analyses of (1) the probability of skipping the target, (2) the relative frequencies of single fixations and of two fixations on a target, (3) the refixation probability of two fixation cases, (4) the landing positions in a target, and (5) fixation times for single fixations and for two fixation cases.

Word skipping. Figure 3 shows the probability of skipping targets as a function of their length. An overall 3 (type of target: HF, LF, or *z*-string) × 5 (target length: 5, 6, 7, 8, or 9 characters) ANOVA yielded significant main effects of type of target word [$F(2,58) = 5.48, p < .01$] and of target length [$F(4,116) = 18.42, p < .001$]. Overall, *z*-strings were skipped more often than were both HF and LF words, and skipping rate systematically decreased from 14.8% to 2.9% with increasing target length. There was also a marginally significant interaction [$F(8,232) = 1.91, p < .06$]. Post hoc tests revealed the following results (Figure 3): With 5-letter and 6-letter targets, the HF words and *z*-strings were skipped equally often and more often than ($p < .05$) LF words; with 7-letter targets, skipping probability was significantly different ($p < .05$) for each type of target word; for the 8-letter and 9-letter targets, the HF and LF words were both skipped less frequently ($p < .05$) than were *z*-strings.

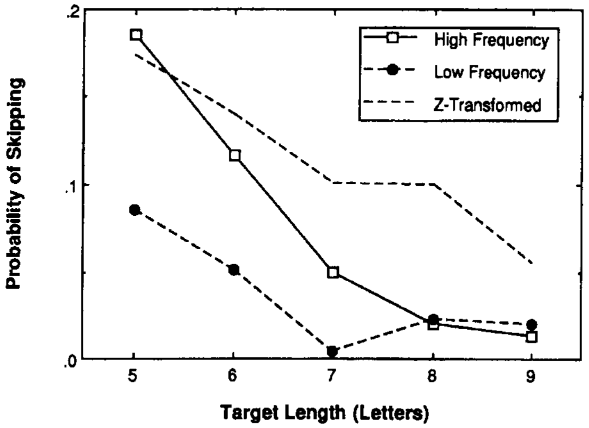

Figure 3. Probability of skipping a high-frequency (white squares), low-frequency (black circles), or *z*-transformed (hatched line) target as a function of its length.

The skipping data clearly reveal two different eye movement strategies for the reading of words and for the scanning of *z*-transformed strings. Consider first the normal reading condition. For long words (8–9 letters), word frequency had little effect on skipping probability. Presumably, readers could not extract enough visual information from such words when they were fixated to the left of them. To process the meaning of these target words, a direct fixation was necessary. For target words that were 5 to 7 letters long, however, readers could occasionally extract enough visual information about the targets parafoveally to process their meaning. Therefore, the probability of skipping these shorter target words increased. The increase was steeper for HF words than for LF words, presumably because the latter were not as familiar to the reader and so could not be fully identified on the basis of parafoveal information alone.

Consider next the scanning condition. With the *z*-transformed text, the missing requirement to identify the target strings led to significantly higher skipping rates for long strings than for long words. Even though short *z*-strings were skipped as often as were short HF words, the increase in skipping probabilities with shorter strings was less than the increase with shorter words. Thus, the comparison between target skipping in the reading and scanning conditions reveals that both visual and lexical factors influenced the eyes' behavior in normal reading, whereas only visual factors affected the eyes during scanning. Moreover, our manipulation of the difficulty of lexically accessing the target word (via the word frequency manipulation) had an immediate effect on eye movement behavior. Consistent with results reported by Rayner et al. (in press; see also Inhoff & Topolski, 1994), the meaning of the word, and more specifically, how easily this meaning could be accessed, immediately influenced the reader's eye behavior.

Frequency of single versus two fixations. One of the problems with the idea of an oculomotor tactic that was mentioned in the Introduction concerned its overemphasis on refixations. Consistent with this criticism we found that, when the target word was fixated, single fixations were considerably more frequent than two fixations on the target word (Table 2). Readers made single fixations more frequently when the target was an HF word than when it was an LF word and, conversely, there were fewer two-fixation cases when the target was an HF word; both effects were significant (*p*s < .01).

These findings are all consistent with data reported by Rayner et al. (in press). They imply that the current lexical processing activity strongly influences the likelihood of a refixation. This is not to say that oculomotor factors are not involved in refixations, because there is clearly an effect of initial landing position in the word (see below). Our point is that lexical processing is a primary factor in whether or not words are refixated. On the basis of these findings we argue that the first fixation on a word is regularly used to acquire lexical information, and that the outcome of this first attempt at lexical access plays a role in the decision where to move the eyes next. To demonstrate this powerful and immediate influence of lexical factors on eye behavior, we next discuss the refixation probabilities when two fixations were made and then present separate analyses of cases with either a single fixation or two fixations on a target string.

Refixation probability of two fixation cases. Figure 4(a–c) shows the probabilities of refixating a target of 5, 6, or 7 characters length, plotted as a function of where in the target the first fixation occurred. Targets that were 8–9 letters long showed similar results, but due to the lack of fixations at the ends of the target strings (Figure 6), the overall pattern was noisier. We therefore do not show refixation probabilities for these word lengths. In general, the data in Figure 4 are consistent with data reported by Vitu et al. (1995) and others (O'Regan, 1992; Rayner et al., in press) in showing that readers are more likely to refixate a word if the initial fixation is at the beginning or end of a word than if the initial fixation is in the middle. From our point of view, the most striking aspect of the data in Figure 4 is that there are systematic differences between the three text conditions when the initial fixation occurred at the end of the target word. Consider first the 5-letter targets. Readers refixated LF words when the initial fixation was at the end, but were much less inclined to do so if the target was either an HF word or a *z*-string. Consider next the 6-character and 7-character targets. When these targets were initially fixated at their ends, both HF and LF words were refixated more often than were the *z*-strings.

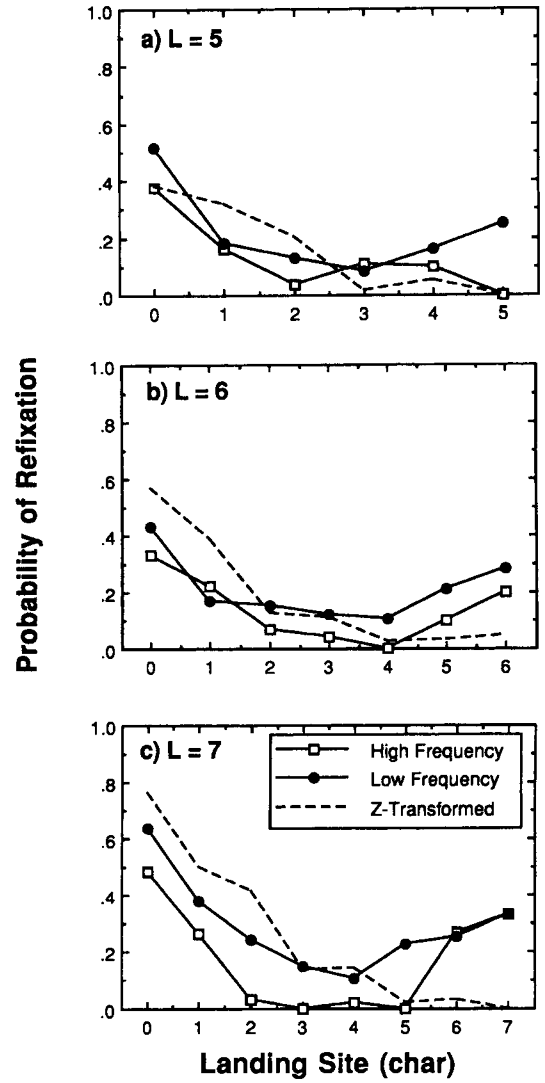

Figure 4. Refixation probabilities. Panels a–c show, for targets of 5, 6, and 7 characters in length, the probability of refixating the target, separately for high-frequency (white squares), low-frequency (black circles), and *z*-transformed (hatched line) targets. Probabilities are plotted at the site of initial fixation, where 0 refers to the space before the target word.

To quantify the spatial behavior of the eyes in the two-fixation cases, we used Vitu et al.'s (1995) zoning algorithm to categorize the initial landing position into beginning, middle, or end of a word. In this case, the algorithm normalized landing positions according to the following formula: (initial fixation position − 0.5)/word length, and then recoded the event in terms of three zones of equal size (⅓). To further overcome problems associated with empty cells, we collapsed across target lengths of 5 and 6 letters to create a short condition and across target lengths of 7, 8, and 9 letters to create a long condition. These data were then submitted to a 3 (type of target: HF, LF, or *z*-string) × 2 (length of target: short vs. long) × 3 (landing zone of first fixation: beginning, middle, or end) ANOVA. This ANOVA yielded significant main effects of type of target [$F(2,58) = 11.89, p < .001$] and of landing zone [$F(2,58) = 8.992, p < .001$], as well as an interaction of these two variables [$F(4,116) = 16.37, p < .001$]. There was no main effect of length and no interaction of length with either of the other variables (all ps > .53). The basic data pattern can be seen in Figure 5.

Post hoc tests to examine the target type × landing zone interaction revealed that there were no differences between conditions when the initial fixation was at the beginning [$F(2,58) = 1.38, p > .25$] or in the middle of the word [$F(2,58) = 1.28, p > .28$]. However, when the initial fixation was at the end of the word, the three conditions differed significantly from one another [$F(2,58) = 21.07, p < .001$]. The post hoc comparisons were as follows: LF versus HF [$F(1,29) = 18.14, p < .001$], LF versus z-string [$F(1,29) = 30.46, p < .001$]; and HF versus z-string [$F(1,29) = 5.24, p < .05$]. As demonstrated previously (Rayner et al., in press), the lexical status of the target word influenced whether or not the word was refixated. The refixation pattern clearly shows that the failure to identify a word from a perceptually suboptimal viewing position induced a refixation in the word. Importantly, the same deviation from an optimal viewing position induced fewer refixations in a meaningless string. This difference illustrates the importance of lexical processing demands for the spatial aspect of oculomotor control and shows that visual factors alone cannot account for the eyes' behavior during reading.

Fixation durations of first and second fixations. In an analysis of the temporal aspects of the eyes' behavior in the two-fixation cases, we compared the durations of first and second fixations as a function of type of target word and word length. This analysis could not be carried out for all 30 subjects since not all made two fixations with sufficient frequency to yield reasonably stable means. Thus, the fixation duration data of 22 subjects who made many dual fixations were analyzed in a 3 (type of target) × 5 (length of target) × 2 (first vs. second fixation) ANOVA. There was a highly significant main effect of type of target [$F(2,21) = 59.39, p < .001$] due to more time spent on the z-strings (average fixation time, 313 msec) than on LF words (244 msec) or HF words (214 msec); all three conditions differed significantly from one another (all ps < .01), and there was no interaction of type of target with first versus second fixation [$F(2,42) = 2.26, p > .10$]. Additionally, first fixations (271 msec) were longer than were second fixations (242 msec) [$F(1,21) = 15.6, p < .001$]. The effect of target length was not significant [$F(4,84) = 2.36, p > .05$], but all of the two-way interactions and the three-way interaction were either significant or marginally significant. These interactions were largely due to unsystematic differences in the z-string condition (i.e., whether the first or second fixation was longer differed slightly as a function of word length) that were not present in the other two conditions (where second fixations were shorter independent of word length). Post hoc comparisons revealed that there was no reliable difference between the first (318-msec) and the second (308-msec) fixation for the z-string condition ($F < 1$). For normal text, however, the average first fixation was longer than was the second fixation, both with HF target words [$F(1,21) = 15.97, p < .01$] and with LF target words [$F(1,21) = 14.06, p < .01$].

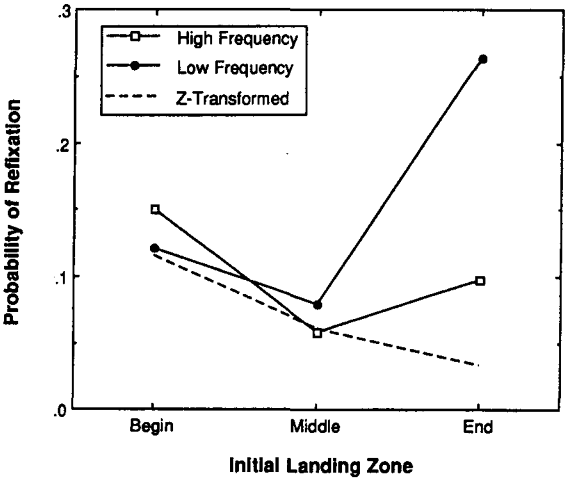

Figure 5. Probability of refixation as a function of the initial landing site, separately for high-frequency (white squares), low-frequency (black circles), and z-transformed (hatched line) targets.

More importantly, there was a frequency effect present in both the first and second fixations. For first fixations, the means were 235 and 260 msec for HF and LF words, respectively [$F(1,21) = 6.70, p < .05$]. For second fixations, the means were 192 and 228 msec, respectively [$F(1,21) = 16.67, p < .001$]. The finding of a frequency effect for both first and second fixation durations is consistent with results reported by Rayner et al. (in press) and points to the importance of lexical processing for temporal aspects of oculomotor behavior.

Landing positions of single fixations. Figure 6(a–e) shows, for all single fixation cases, the landing position of the eyes on the targets as a function of target length and type of target. Like many researchers before us, we found a moderate preference to fixate a word in the middle rather than at its beginning or end (see, e.g., McConkie et al., 1988; O'Regan, 1990; Rayner, 1979). More importantly for the present issue, and consistent with results reported by Rayner et al. (in press), there was generally no difference in where readers landed as a function of target type. We determined, at each character position of each target and at the empty space before each target, the effect of target type (HF, LF, or z-string) on the percentage of single fixations. We performed a total of 40 simple effects tests, only five of which yielded reliable differences. These results are quite consistent with Vitu et al.'s (1995) finding of no reliable differences in landing sites between the normal and transformed texts.

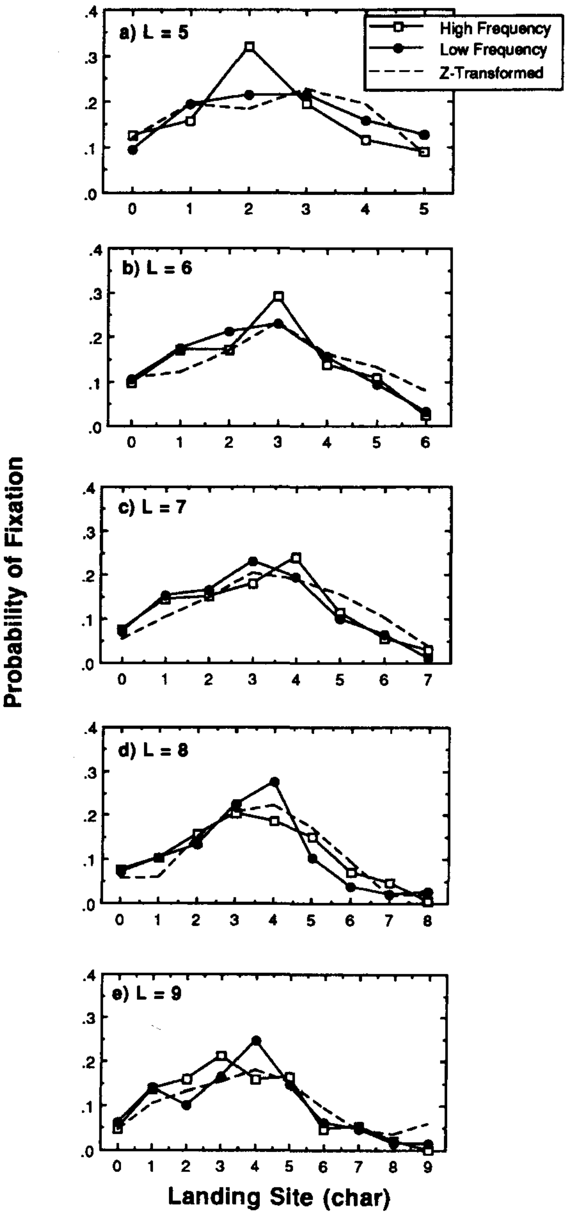

Figure 6. Single fixation cases. Landing positions for targets of 5 to 9 characters in length are shown in panels a–e, separately for high-frequency (white squares), low-frequency (black circles), and *z*-transformed (hatched line) targets.

Single fixation durations. Figure 7(a–c) shows the average durations of single fixations as a function of target length for words that were 5–7 letters long; again, because infrequent fixations at the ends of words of 8–9 letters resulted in noisy data, fixation durations are not shown for these word lengths. Figure 7(d) shows the data for all string lengths, but averaged across landing sites. The *z*-transformation of the text resulted in longer single fixations than did either of the normal text conditions. A 3 (type of target) × 5 (length of target) ANOVA on these data yielded a highly significant effect of target type $[F(2,58) = 19.33, p < .001]$ and an effect of length $[F(4,116) = 2.73, p < .05]$, with no interaction $(F < 1)$.

To further evaluate the impact of the stimulus material on the landing position of the eyes, each landing position was converted into one of five zones using Vitu et al.'s (1995) zoning algorithm; the algorithm normalized landing positions according to the following formula: (initial fixation position − 0.5)/word length; the

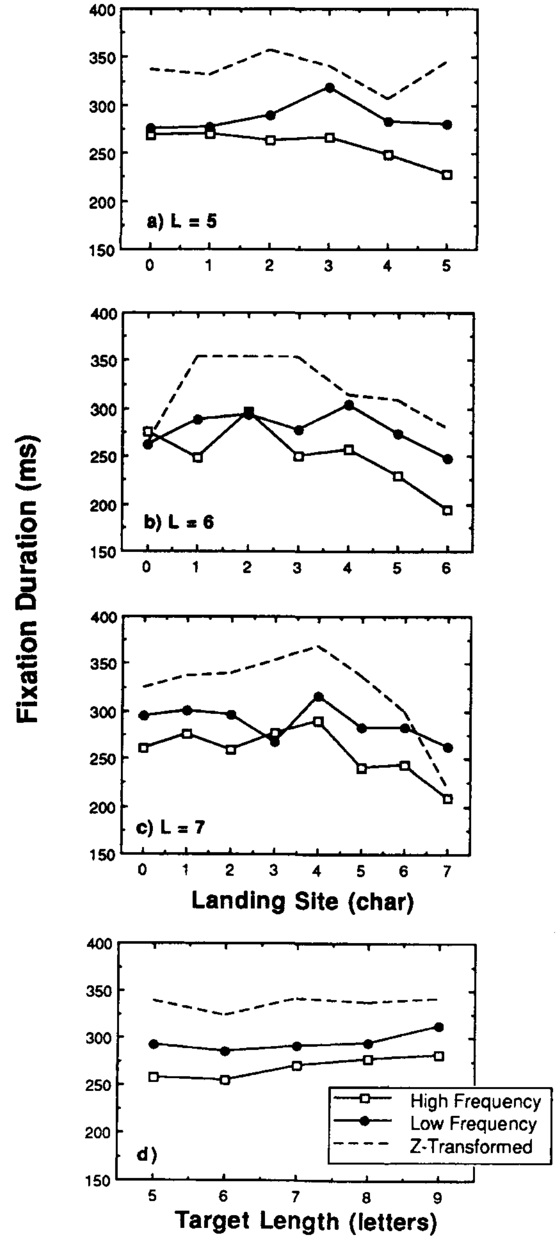

Figure 7. Single fixation cases. Fixation durations for targets of 5 to 7 characters in length are shown in panels a–c, separately for high-frequency (white squares), low-frequency (black circles), and *z*-transformed (hatched line) targets. Panel d shows fixation durations for all target lengths, but averaged across landing positions.

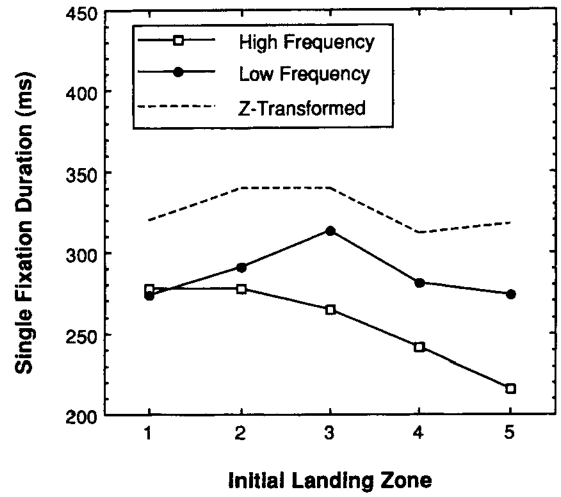

Figure 8. Single fixation cases. Fixation durations as a function of landing zone for high-frequency (white squares), low-frequency (black circles), and *z*-string (hatched line) targets.

algorithm then recoded the event in terms of five zones of equal size (⅕). We then performed a 3 (target type) × 5 (landing zone) ANOVA that yielded significant main effects of both variables and a significant interaction (Figure 8). Specifically, subjects fixated longer on *z*-strings (326 msec) than on LF words (287 msec) than on HF words (255 msec) [$F(2,58) = 28.69, p < .001$]; all pairwise comparisons were significant ($p < .01$). Subjects also fixated longer on average on the second and third zones (303 and 306 msec, respectively) than on the fourth and fifth zones (278 and 269 msec, respectively) [$F(4,116) = 6.34, p < .01$]; all interset comparisons were significant ($p < .01$). Finally, the effect of landing position on single fixation durations was present with words, but not *z*-strings [$F(8,232) = 2.62, p < .01$]. Simple effects tests confirmed that the durations of single fixations were not reliably affected by landing position in the *z*-strings [$F(4,116) = 1.20, p > .30$], but they were reliably affected by landing position on the HF words [$F(4,116) = 11.31, p < .001$] and on the LF words [$F(4,116) = 4.17, p < .01$].

In summary, the single fixation data in Figures 7 and 8 are quite consistent with those reported previously by Rayner et al. (in press) in demonstrating a word frequency effect on single fixation durations. This result shows that lexical processing clearly affects the duration of single fixations. From the absence of systematic differences in the landing positions (see above) we can further infer that the frequency effect on fixation durations is independent of the landing position of the eyes.

Gaze duration. Gaze duration reflects the fixation time on a word before the eyes move on to the next word. Thus, the measure is a mixture of single fixation cases, two fixation cases, and (a few) cases with more than two fixations (see Table 2 for proportions). A 3 (type of target) × 5 (target length) ANOVA on the gaze duration data yielded significant main effects for type of target [$F(2,58) = 10.21, p < .001$] and for target length [$F(4,116) = 27.37, p < .001$], and no significant interaction [$F(8,232) = 1.47, p > .17$]. The data are plotted in Figure 9, which shows that the effect of word frequency was quite consistent across word lengths.

Visual search versus reading. We turn now to a comparison of the visual search condition with the other conditions in the experiment. The comparison between the search condition and the reading condition is important because it allowed us to compare processing associated with the target words (the HF and LF words) when there was a need for lexical processing (reading) and when such processing was not necessary (search). As noted earlier, our primary interest in the search condition was in the trials in which the word *zebra* was not present in the sentence. On such trials, subjects searched to the end of the sentence and then pushed a button indicating that *zebra* was not present. These sentences contained either an HF or an LF word so that we could determine whether or not there was a frequency effect on these target words. To this end, we examined single fixation duration, gaze duration, and the probability of skipping the target word. Thus, 2 (word frequency) × 5 (word length) ANOVAs were carried out on these data. The data from all three analyses were quite consistent in demonstrating no frequency effect on any of the measures; [the F values for single fixation duration and skipping probability were both less than 1, and for gaze duration, $F(1,9) = 1.31$, $p > .25$]. For single fixation duration, the means were 214 msec for HF words and 210 msec for LF words; for gaze duration, the means were 218 msec for HF and 215 msec for LF words; the skipping rates were 34% for HF and 38% for LF words. Not surprisingly, word length influenced both the probability of skipping [$F(4,36) = 9.33, p < .001$] and gaze duration [$F(4,36) = 2.77, p < .05$]. Skipping rates were higher for 5-letter words (57%) than for 8- and 9-letter words (19% and 20%, respectively), while the skipping rates for 6- and 7-letter words were intermediate (39% and 43%, respectively). Gaze durations ranged from 210 msec for 5-letter words to 225 msec for 9-letter words.

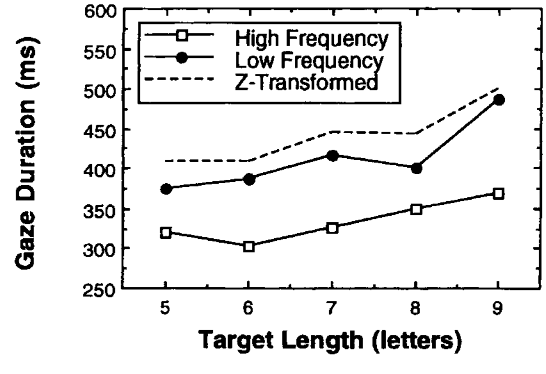

Figure 9. Gaze durations as a function of target length, separately for high-frequency (white squares), low-frequency (black circles), and *z*-transformed (hatched line) targets.

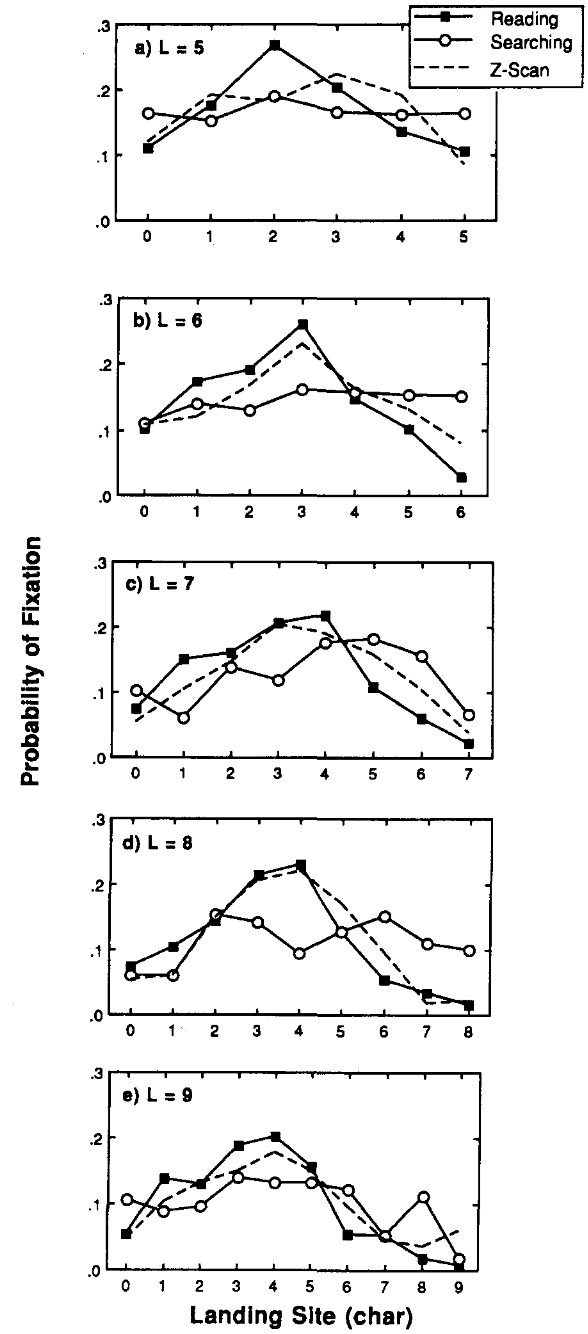

Figure 10. Distribution of landing sites of single fixations during reading, *z*-string scanning, and visual search for the word *zebra*. Data are averaged across high-frequency and low-frequency targets.

Figure 10 shows the landing site data for the search condition in comparison with the normal reading and *z*-string conditions. In this figure, we have collapsed across HF and LF target words since there was no difference in the pattern in either reading or search between the two types of words. It is interesting to note that for 5- and 6-letter words, the landing site function is fairly flat in the search task. The function is less flat for 7-, 8-, and 9-letter words, but it is obviously different from the reading data. Interestingly, with the possible exception of the 5-letter word data, the *z*-string reading data on landing sites look more like the normal reading data than do the search data.

To quantify these data, we used Vitu et al.'s (1995) zoning algorithm to create five zones for the landing sites; a 3 (task) × 5 (landing zone) ANOVA was carried out on the data. This analysis yielded a significant effect of landing zone [$F(4,268) = 58.68, p < .001$] and a significant interaction [$F(8,268) = 4.02, p < .001$] that is apparent in Figure 11, which shows that the search condition differed from the other two conditions.

Our assumption that subjects were not processing the meaning of the sentences in the search condition was examined via a surprise test at the end of the experiment in which subjects were given a list of 20 sentences and asked to indicate if the sentence had appeared in the experiment. Subjects in the search condition were correct 55% of the time; a t test revealed that their performance was not different from chance [$t(9) = 1.25, p > .2$]. Their performance was also compared to that of 10 readers who were given the same test after reading the same sentences. These readers (who were not in the other conditions, but were from the same population pool) were correct 76% of the time; the difference between the two groups was significant [$t(18) = 3.45, p < .01$].

GENERAL DISCUSSION

The present study was an extension of a study recently reported by Vitu et al. (1995). The issue under investigation was whether spatial and temporal characteristics of eye movement behavior during reading can best be accounted for by low-level visuomotor factors or by the lexical processing demands on the reader. In both studies, subjects were asked to read normal text and to pretend that they were reading strings of *z*-transformed text.

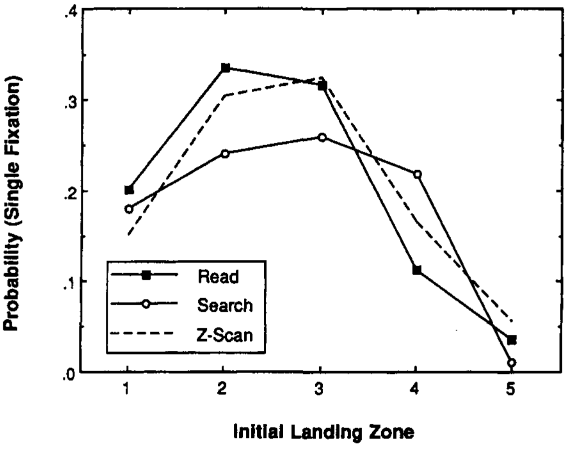

Figure 11. Probability of landing in different landing zones as a function of task.

The latter condition was meant to provide information about oculomotor behavior in the absence of lexical processing demands that can be compared against the eye behavior of the same readers in a normal reading task. Based on their global analyses, Vitu et al. (1995) concluded that eye movement characteristics are similar when subjects read or scan *z*-strings. Although they were appropriately cautious in acknowledging that factors related to the ongoing lexical processing of the fixated word are important for the spatial and temporal control of eye movements, the primary gist of their article is that eye movement behavior in the two situations is remarkably similar. Our data, on the other hand, lead us to conclude that while there are some similarities, for the most part the eye movement characteristics (particularly fixation times) are quite different for reading and *z*-string scanning. Specific differences between the two conditions were observed in terms of (1) word skipping, (2) fixation times, and (3) refixation probabilities.

With respect to word skipping, we found that how easy the meaning of a word was to access determined word skipping, whereas for *z*-strings the length of the string determined the probability of skipping. For words that were 5–7 letters long, HF words were skipped more often than were LF words. We assume that this was because the meaning of the HF word could be determined more readily when readers were fixated just prior to the beginning of the word than was the case when they were fixated just to the left of the beginning of an LF word. For words that were longer (8–9 letters), because of acuity limitations the entire word could not be processed when readers were fixated just to its left, and hence word frequency had no effect on skipping.

The fixation time data also yielded very clear effects of word frequency. As previously demonstrated by Rayner et al. (in press), we found that in the case of single fixations on words, there was a frequency effect that was independent of the landing position; *z*-string scanning, on the other hand, yielded longer fixations than either HF or LF words. We also found that, for both HF and LF words, when two fixations were made on the target word, the first fixation was longer than the second fixation. For *z*-string scanning, on the other hand, there was no difference between the duration of the first and second fixation. Also, it is important to note that, like Rayner et al. (in press), we found a frequency effect on the first and second fixations. This result, as well as the finding that the frequency effect is independent of landing position in a word, is inconsistent with O'Regan's (1990, 1992) oculomotor model (see Rayner et al., in press, for further discussion).

Finally, with respect to the comparison of reading and *z*-string scanning, we found that refixation probabilities differed for the two situations. Whether or not there was a refixation (a second fixation on the target word before moving to another word) was very much influenced by the characteristics of that word. Specifically, subjects did not refixate when they landed on the ends of *z*-strings, whereas they did refixate after an initial fixation at the ends of words. Presumably, in order to comprehend the target word, it was often necessary to make a second fixation following an initial fixation at the end of the word. In the *z*-string condition, it was impossible to meaningfully process the target word and, hence, refixations were not necessary.

From the analyses on the visual search data (fixation times and skipping probabilities) and from comparing the landing site data, it appears to us that the visual search and *z*-string scanning data are similar in terms of fixation times. Importantly, without the need to process the meaning of words there was no frequency effect even when subjects looked at lexically meaningful material (see also Rayner & Raney, 1996). This lack of a frequency effect in the search task is in marked contrast to normal reading, where there was a highly robust frequency effect, and is consistent with the hypothesis that the trigger to move the eyes in a visual search task is different from that in reading (Rayner, 1995). Our examination of landing positions also showed that the search data were quite different from the reading data; the landing position curves (particularly for 5- to 6-letter words) were quite flat and did not show more fixations near the middles of words, as is typically found in reading. The *z*-string landing site data, however, looked more like reading than search. Perhaps the instruction to "pretend" to read the *z*-strings encouraged the subjects to program saccades that are more typical of reading than of search.

Most readers have probably had the experience of moving their eyes across text while at the same time their mind wandered so that nothing was comprehended from the text. This "daydream mode" would be very difficult to study experimentally. Thus, Vitu et al. (1995) instead studied the characteristics of eye movements in a "mindless reading" situation without linguistic information to be processed. Their analysis showed, and our data confirm, that the decision about where to fixate next is fairly similar in the two situations. Thus, a number of global aspects of eye movement behavior, as well as landing position effects, were quite similar in the two situations. It is, however, not surprising that a lifetime of reading habits yields eye movement patterns with some resemblance to reading (in terms of the global behavior). On the other hand, our data show quite clearly that decisions about when to move the eyes are strongly influenced by the ongoing linguistic processing. Specifically, (1) the highly robust frequency effect in normal reading, (2) the differences in fixation times between *z*-string scanning and normal reading, and (3) the lack of a frequency effect in the visual search task all demonstrate that there are marked differences in when the eyes move as a function of whether or not linguistic processing is necessary (or possible). Additionally, our data demonstrate that some decisions about where to fixate next are also influenced by the ongoing linguistic processing. In particular, we found word skipping and the probability of making a refixation to be strongly influenced by word frequency.

In summary, the data presented here suggest that the oculomotor type of model may be able to account for some aspects of where readers fixate. It does, however, not do a good job of accounting for when readers move their eyes. These two decisions (when and where) are considered to be somewhat independent in processing models, while they are not independently made according to oculomotor models. The hypothetical eye fixation tactics module proposed by O'Regan (1990, 1992) addresses specifically two-fixation cases and thus deals with only a small subset of the overall eye behavior in reading. For all these reasons, we conclude that the processing type of model is to be preferred over the oculomotor model in accounting for eye movement behavior in reading.

REFERENCES

Balota, D. A., Pollatsek, A., & Rayner, K. (1985). The interaction of contextual constraints and parafoveal visual information in reading. *Cognitive Psychology*, **17**, 364-390.

Ehrlich, S. F., & Rayner, K. (1981). Contextual effects on word perception and eye movements during reading. *Journal of Verbal Learning & Verbal Behavior*, **20**, 641-655.

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

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

Hogaboam, T. W. (1983). Reading patterns in eye movement data. In K. Rayner (Ed.), *Eye movements in reading: Perceptual and language processes* (pp. 309-332). New York: Academic Press.

Inhoff, A. W. (1984). Two stages of word processing during eye fixations in the reading of prose. *Journal of Verbal Learning & Verbal Behavior*, **23**, 612-624.

Inhoff, A. W. (1989). Parafoveal processing of words and saccade computation during eye fixations in reading. *Journal of Experimental Psychology: Human Perception & Performance*, **15**, 544-555.

Inhoff, A. W., & Rayner, K. (1986). Parafoveal word processing during eye fixations in reading: Effects of word frequency. *Perception & Psychophysics*, **40**, 431-439.

Inhoff, A. W., & Topolski, R. (1994). Use of phonological codes during eye fixations in reading and in on-line and delayed naming tasks. *Journal of Memory & Language*, **33**, 689-713.

Inhoff, A. W., Topolski, R., Vitu, F., & O'Regan, J. K. (1993). Attention demands during reading and the occurrence of brief (express) fixations. *Perception & Psychophysics*, **54**, 814-823.

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

Morrison, R. E. (1984). Manipulation of stimulus onset delay in reading: Evidence for parallel programming of saccades. *Journal of Experimental Psychology: Human Perception & Performance*, **10**, 667-682.

O'Regan, J. K. (1979). Saccade size control in reading: Evidence for the linguistic control hypothesis. *Perception & Psychophysics*, **25**, 501-509.

O'Regan, J. K. (1990). Eye movements and reading. In E. Kowler (Ed.), *Eye movements and their role in visual and cognitive processes* (pp. 395-453). Amsterdam: Elsevier, North-Holland.

O'Regan, J. K. (1992). Optimal viewing position in words and the strategy-tactics theory of eye movements in reading. In K. Rayner (Ed.), *Eye movements and visual cognition: Scene perception and reading* (pp. 333-354). New York: Springer-Verlag.

Pollatsek, A., & Rayner, K. (1990). Eye movements and lexical access in reading. In D. A. Balota, G. B. Flores d'Arcais, & K. Rayner (Eds.), *Comprehension processes in reading* (pp. 143-163). Hillsdale, NJ: Erlbaum.

Pollatsek, A., Rayner, K., & Balota, D. A. (1986). Inferences about eye movement control from the perceptual span in reading. *Perception & Psychophysics*, **40**, 123-130.

Radach, R., & Kempe, V. (1993). An individual analysis of initial fixation positions in reading. In G. d'Ydewalle & J. van Rensbergen (Eds.), *Perception and cognition: Advances in eye movement research* (pp. 213-226). Amsterdam: Elsevier, North-Holland.

Raney, G. E., & Rayner, K. (1995). Word frequency effects and eye movements during two readings of a text. *Canadian Journal of Experimental Psychology*, **49**, 151-172.

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

Rayner, K. (1995). Eye movements and cognitive processes in reading, visual search, and scene perception. In J. M. Findlay, R. W. Kentridge, & R. Walker (Eds.), *Eye movement research: Mechanisms, processes and applications* (pp. 3-22). Amsterdam: Elsevier, North-Holland.

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

Rayner, K., & McConkie, G. W. (1976). What guides a reader's eye movements? *Vision Research*, **16**, 829-837.

Rayner, K., & Morris, R. K. (1992). Eye movements in reading: Evidence against semantic preprocessing. *Journal of Experimental Psychology: Human Perception & Performance*, **7**, 167-179.

Rayner, K., & Pollatsek, A. (1987). Eye movements in reading: A tutorial review. In M. Coltheart (Ed.), *Attention and performance XII: The psychology of reading* (pp. 327-362). Hillsdale, NJ: Erlbaum.

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

Rayner, K., & Raney, G. E. (1996). Eye movement control in reading and visual search: Effects of word frequency. *Psychonomic Bulletin & Review*, **3**, 245-248.

Rayner, K., & Sereno, S. C. (1994). Eye movements in reading: Psycholinguistic studies. In M. A. Gernsbacher (Ed.), *Handbook of psycholinguistics* (pp. 57-81). San Diego: Academic Press.

Rayner, K., Sereno, S. C., Morris, R. K., Schmauder, A. R., & Clifton, C., Jr. (1989). Eye movements and on-line language comprehension processes. *Language & Cognitive Processes*, **4**, 21-49.

Rayner, K., Sereno, S. C., & Raney, G. E. (in press). Eye movement control in reading: A comparison of two types of models. *Journal of Experimental Psychology: Human Perception & Performance*.

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

Salthouse, T. A., & Ellis, C. L. (1980). Determinants of eye fixation duration. *Journal of Experimental Psychology: Human Perception & Performance*, **7**, 611-623.

Sereno, S. C. (1992). Early lexical effects when fixating a word in reading. In K. Rayner (Ed.), *Eye movements and visual cognition: Scene perception and reading* (pp. 304-316). New York: Springer-Verlag.

Vitu, F. (1991). The influence of parafoveal processing and linguistic context on the optimal landing position effect. *Perception & Psychophysics*, **50**, 58-75.

Vitu, F. (1993). The influence of the reading rhythm on the optimal landing position effect. In G. d'Ydewalle & J. Van Rensbergen (Eds.), *Perception and cognition: Advances in eye movement research* (pp. 181-192). Amsterdam: Elsevier, North-Holland.

Vitu, F., O'Regan, J. K., Inhoff, A. W., & Topolski, R. (1995). Mindless reading: Eye movement characteristics are similar in scanning letter strings and reading texts. *Perception & Psychophysics*, **57**, 352-364.

Vitu, F., O'Regan, J. K., & Mittau, M. (1990). Optimal landing position in reading isolated words and continuous text. *Perception & Psychophysics*, **47**, 583-600.

Zola, D. (1984). Redundancy and word perception during reading. *Perception & Psychophysics*, **36**, 277-284.

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