Eye Movement Control During Reading: Fixation Measures Reflect Foveal but Not Parafoveal Processing Difficulty

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Abstract The main purpose of this study was to determine whether, during natural reading, the difficulty of the upcoming parafoveal word affects eye movement behaviour on the currently fixated word. A model in which visual attention is allocated in parallel over both the fixated and the upcoming parafoveal word predicts such an effect, while a sequential attention allocation model in which attention is directed first to the fixated word and then to the upcoming parafoveal word, does not. The data reported here show that neither the frequency nor the combined length, frequency and class of the upcoming word affect eye movement behaviour on the current word. These data support the sequential attention – parallel programming model of eye movement control in reading.

Résumé L'étude que nous avons réalisée avait pour principal objet de déterminer si, durant la lecture naturelle, la difficulté que pose le mot périfovéal suivant influence la fixation oculaire sur le mot fovéal. Un modèle dans lequel l'attention visuelle se porte parallèlement sur le mot fixé et sur le mot périfovéal suivant prédit un tel effet, mais non un modèle de répartition séquentielle dans lequel l'attention est d'abord dirigée vers le mot fixé, puis vers le mot périfovéal suivant. D'après les données recueillies, ni la fréquence ni la combinaison de la longueur, de la fréquence et de la classe du mot suivant n'influencent la fixation sur le mot fovéal. Ces données appuient le modèle de programmation parallèle – attention séquentielle relativement au contrôle des mouvements oculaires durant la lecture.

Recently, studies employing eye movement recording techniques have provided a great deal of insight into the nature of the reading process (for reviews, see Just & Carpenter, 1987; Rayner & Pollatsek, 1989). In an innovative use of eye movement recording, McConkie and Rayner (1975) introduced the "moving window" paradigm, in which the amount of text presented to the reader during any given fixation is directly manipulated by

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changing the display as a function of eye position. Text within the window region is displayed normally, while text outside of the window is mutilated in some way (e.g., replaced with X's). According to the logic of the paradigm, if information that is typically acquired during a fixation is outside of the window (i.e., mutilated), then reading will be disrupted. On the other hand, if the information outside of the window is not typically acquired, then the mutilation beyond the window should produce no disruption. Using this paradigm, researchers have shown that the *perceptual span* in reading (the region from which useful information is acquired during an eye fixation) is asymmetric, extending from a maximum of about 4 character spaces to the left of the currently fixated character (McConkie & Rayner, 1976; Rayner, Well, & Pollatsek, 1980; Underwood & McConkie, 1985) to a maximum of about 15 character spaces to the right (McConkie & Rayner, 1975; Rayner, Inhoff, Morrison, Slowiaczek, & Bertera, 1981).

One explanation of the asymmetric nature of the perceptual span in reading is that the allocation of visual-spatial attention partially controls the acquisition of information during each eye fixation (Henderson & Ferreira, 1990; McConkie, 1979; Morrison, 1984). In general, it appears that a covert change in the locus of visual-spatial attention precedes an impending saccade to the location about to be fixated (e.g., Bryden, 1961; Crovitz & Daves, 1962; Henderson, 1993; Henderson, Pollatsek, & Rayner, 1989; Rayner, McConkie, & Ehrlich, 1978; Remington, 1980; Shepherd, Findlay, & Hockey, 1986; for a review, see Henderson, 1992). In reading, evidence supporting the hypothesis that the asymmetry of the perceptual span is due to attentional factors is provided by studies showing that the direction of the perceptual span reverses when the text is read from right to left. For example, Pollatsek, Bolozky, Well, and Rayner (1981) found that the perceptual span for readers fluent in both English and Hebrew was asymmetric to the right when they were reading English, but asymmetric to the left when they were reading Hebrew. Because Hebrew is read from right to left, these results indicate that more information was acquired in the direction that the eyes were generally moving through the text. Similarly, Inhoff, Pollatsek, Posner, & Rayner (1989) found that when readers of English were asked to read text backward (i.e., from right to left), then the asymmetry of the perceptual span reversed, so that more information was acquired from locations to the left of the current fixation point. The finding that the direction of the perceptual span changes depending on the direction of reading (Pollatsek et al., 1981), and that this change does not result from long-term learning (Inhoff et al., 1989), suggests that a dynamic attentional component is involved in defining the nature of the perceptual span in reading.

ATTENTION AND EYE MOVEMENT CONTROL IN READING

To account for eye movement control in reading, Morrison (1984) proposed the *parallel programming model* (for variations on the theme, see also Henderson, 1992; Henderson, Pollatsek, & Rayner, 1989; Henderson & Ferreira, 1990; McConkie, 1979; Pollatsek & Rayner, 1990). According to this model, each fixation begins with visual attention focussed on the word currently centred at the fovea. After processing of the foveal word has reached a criterion level of completion, attention shifts to the parafoveal word to the right of the foveal word. The shift of attention gates processing of the word at the newly attended location and signals the eye movement system to prepare a program to move the eyes. The motor program is executed once it is completed, and the eyes then follow attention to the new word. Because there is a time lag between the shift of attention and the movement of the eyes due to the programming latency, information is acquired from the parafoveal word before it is fixated. Attention will sometimes shift again to the word beyond the parafoveal word if the parafoveal word is relatively easy to identify (Morrison, 1984). In these cases, the eye movement program will be changed to send the eyes two words to the right and the parafoveal word will be skipped. Thus, the perceptual span will sometimes include two words to the right of the currently fixated word. Furthermore, because attention precedes the eyes to the word that the eyes will move to next, the asymmetric nature of the perceptual span can be accounted for; information is acquired from locations that are in the direction that the eyes are moving.

The original Morrison model of eye movement control predicted that the amount of information acquired from the parafoveal word to the right of fixation should remain constant regardless of the difficulty of the foveal word. This prediction followed because attention was assumed not to shift to the parafoveal word until the criterion level of processing was reached for the foveal word (see discussion in Henderson, 1992). Thus, if the foveal word were more difficult, then the criterion would take longer to reach and the fixation on the foveal word would be longer. However, because attention would remain on the foveal word, this additional fixation time would not benefit the parafoveal word. When the criterion was finally reached, attention would shift, programming would begin, and the eyes would follow by the constant programming latency.

Initial evidence that the constant preview prediction was wrong was provided by Rayner (1986). Using the moving window paradigm, Rayner (1986) found that the average perceptual span of a beginning reader was about 20% smaller than that of a skilled reader, and that the average size of the perceptual span was further reduced as text difficulty increased. On the assumption that both reading skill and text difficulty increase foveal processing difficulty, these results can be taken to suggest that as foveal load increases (due to less skill or more difficult text), the perceptual span decreases. Unfortunately, a potential problem with this interpretation of the Rayner study is that foveal load and extrafoveal load covaried; for the less skilled readers and for the more difficult text, the difficulty of words appearing both at fixation and beyond fixation increased together. Therefore, it was impossible to determine whether the perceptual span decreased because of increases in foveal difficulty or increases in extrafoveal difficulty.

In order to examine more directly the effect of foveal load on the perceptual span, Henderson and Ferreira (1990) manipulated foveal difficulty in a paradigm that held extrafoveal difficulty constant. In that study, we had subjects read simple sentences for meaning. We asked whether increasing the difficulty of the currently fixated (foveal) word in a sentence would reduce the amount of information acquired from the (parafoveal) word to be fixated next. We employed the *boundary* technique, in which the letter string occupying the target position is changed when the eyes cross an invisible boundary in the text (Rayner, 1975). Using this technique, we were able to manipulate independently foveal difficulty and the availability of a preview of the parafoveal target prior to fixation on the target. We found that increasing the difficulty of the foveal word through either lexical frequency (defined by Kucera and Francis, 1967, norms) or syntactic difficulty (defined by parsing strategies; see Ferreira & Henderson, 1990, this volume) decreased the amount of information acquired from the parafoveal target. This result provided direct evidence that increasing the foveal load decreased the effective size of the perceptual span during reading, contrary to the Morrison model.

There are two ways in which the parallel programming model might be modified in order to account for the effect of foveal load on the preview benefit (Henderson, 1992). First, according to the *parallel allocation* hypothesis, during an eye fixation attention is allocated simultaneously to both the foveal word and the word about to be fixated next. For example, attention might be thought of as an elongated spotlight or gradient covering the foveal and parafoveal words (Eriksen & St. James, 1986; Henderson, 1991). On this view, increasing foveal load decreases the amount of information acquired from the parafoveal word because the spotlight or gradient-peak shrinks as foveal load increases. Second, according to the *sequential allocation with decoupling* hypothesis, attention is normally directed to the foveal word and then the extrafoveal word in a sequential manner, but when foveal processing is difficult, initial programming of the eye movement to the parafoveal word sometimes begins prior to the shift of attention to that word so that the attentional shift and the initiation of eye movement programming are decoupled (Henderson, 1988; Henderson & Ferreira, 1990; Pollatsek & Rayner, 1990). On this view, attention would shift to the parafoveal word after the eye movement programming had already started but prior to the saccade, leading to a reduced time lag between the attentional shift and the saccade, and thus to a reduced preview benefit.

One way to distinguish between the parallel allocation hypothesis and the sequential allocation with decoupling hypothesis would be to determine whether parafoveal processing difficulty affects eye movement behaviour on the currently fixated word. According to the parallel allocation hypothesis, we would expect to observe some effect of parafoveal difficulty, given that attention is being shared between the foveal and parafoveal words (and assuming that parafoveal processing is resource limited). On the other hand, according to the sequential allocation with decoupling hypothesis, parafoveal difficulty should not affect eye movement behaviour on the current word because fixation behaviour on the current word is determined before the next word is attended.

Three previous studies provide some data on the issue of whether parafoveal difficulty affects eye movement behaviour on the current word. First, Rayner (1975) reported that fixations were longer on a word during reading if that word were followed by a non-word than by a regular word, but *only if the fixation on the current word was on the final two letters or the* space between the words. Second, Blanchard, Pollatsek, and Rayner (1989) reported a study in which they alternated the size of the window of text available to the reader from fixation to fixation. On some fixations the foveal word and the next word were available, while on other fixations only the foveal word was available, while the parafoveal word was replaced with a visual mask. They found that the availability of word information in the parafovea had no effect on the duration of the fixation on the current word. Similarly, in the Henderson and Ferreira (1990) study discussed above, the stimulus available at position $n + 1$ during fixation on word n was either a word or a nonsense letter string. Again, the finding was that parafoveal word information had no effect on the duration of the fixation on the current word. Together, the latter two studies provide evidence against the parallel allocation hypothesis, as does the Rayner study for cases where the fixation is not at the very end of the current word. However, this interpretation depends on the assumption that parafoveal processing difficulty differs as a function of whether there is a word or something else (a mask or nonsense letter string) in the parafovea. Unfortunately, we have no way to know whether or not this assumption is correct. The present experiment seeks to circumvent this problem by manipulating parafoveal difficulty in a more straightforward manner via lexical complexity.

Experiment

The main purpose of the present study was to examine further the degree to which the difficulty of the *next* word (word $n + 1$) would affect eye movement measures during fixation on the current word n. In order to explore *this question, we examined the effects of parafoveal difficulty on the* processing of the currently fixated word in natural reading. We manipulated parafoveal difficulty using lexical factors, so that the parafoveal stimulus in both the easy and difficult conditions was a word. More specifically, we used two manipulations of parafoveal difficulty. First, we examined the effects of lexical frequency, holding word length and lexical class constant. Second, as a more extreme test, we examined a combination of lexical frequency, lexical class, and length. For this second manipulation, we contrasted short, high frequency, closed class words against longer, lower frequency, open class words. According to the parallel allocation hypothesis, we would expect some effect of the difficulty of word *n + 1* during the fixation of word *n*. According to the sequential attention hypothesis, on the other hand, the difficulty of word *n + 1* should not affect fixation measures during fixation on word *n*.

We also wanted to ensure that the properties of the currently fixated word were able to affect eye movement behaviour on that word. If we did not find an effect of word *n + 1* difficulty on word *n* processing, it would be important to demonstrate that word *n + 1* difficulty did affect processing of that word itself when it is fixated, in order to show that difficulty was adequately manipulated, and also to show that processing of that word was resource limited. Based on many previous experiments, we expected that the difficulty of the currently fixated word would be reflected in both initial and later processing measures. For example, the lexical frequency of a word has been shown to affect eye movement behaviour on that word (Henderson & Ferreira, 1990; Just & Carpenter, 1980; Rayner, 1977; Rayner & Duffy, 1986). Therefore, we expected that high frequency words would be fixated for less time than low frequency words.

In the present experiment, we will be interested in eye movement behaviour on three words in each sentence. For example, consider the sentences presented in Table 1. In each sentence, *Word 1* refers to the word prior to the first manipulated word, *Word 2* refers to the first manipulated word, and *Word 3* refers to the second manipulated word. The primary question is whether eye movement behaviour on Word 1 is affected by the difficulty (frequency) of Word 2, and whether eye movement behaviour on Word 2 is affected by the difficulty (length, frequency, and syntactic class) of Word 3. Second, in order to test our difficulty manipulations, we will want to examine whether eye movement behaviour on Word 2 is affected by the difficulty of Word 2, and whether eye movement behaviour on Word 3 is affected by the difficulty of Word 3. Finally, we want to determine whether Word 3 will be skipped more when it is short, high-frequency, and closed-class, given that the immediately preceding word is controlled.

METHOD

Subjects

Twenty-four undergraduate and graduate students at the University of Alberta were paid $6.00 to participate in the study. The participants had normal or corrected-to-normal vision. Those with corrected vision wore contact lenses during the study.

TABLE 1
Example sentence frames with each of the two difficulty manipulations. Word 1 is indicated by underline, *Word 2* by italics, and **Word 3** by bold.

Easy (high-frequency) Word 2, easy (closed-class) Word 3
I decided to wait <u>until</u> *winter* **to** use my fireplace.
Easy (high-frequency) Word 2, difficult (open-class) Word 3
Working outdoors in <u>the</u> *winter* **cold** is not fun.
Difficult (low-frequency) Word 2, easy (closed-class) Word 3
I decided to wait <u>until</u> *autumn* **to** use my fireplace.
Difficult (low-frequency) Word 2, difficult (closed-class) Word 3
Working outdoors in <u>the</u> *autumn* **cold** is not fun.

Apparatus

Eye movements were monitored via an ISCAN RK-416 eyetracker. Signals from the eyetracker were sampled at a frequency of 60 Hz. Sentences were displayed on a high-resolution, flat-screen monitor, white letters on a black background. At a viewing distance of 36 cm, each letter subtended about 1/3 degree of visual angle. The eyetracker and display were interfaced with an 80386 microcomputer that controlled the experiment. The computer kept a complete eye movement record, including fixation positions and durations.

Materials

Word 2 consisted of 36 pairs of words that varied in lexical frequency, as assessed by the Kucera and Francis (1967) norms. These were the same words used in Experiment 1 of Henderson and Ferreira (1990), and are given in the appendix to that paper. The mean frequencies were 148 and 12 counts per million for the high- and low-frequency words, respectively. The words in each pair were either synonyms or closely related words (e.g., winter, autumn) and were matched on word length. Word 3 consisted of 36 pairs of long, low frequency, open class and short, high frequency, closed class words.

For each Word 2 pair, two sentence frames were constructed. Both members of a Word 2 pair formed a coherent sentence when entered into either frame. One of the two sentence frames contained a short, high frequency, closed class member of a Word 3 pair immediately following the position of Word 2, while the other sentence frame contained the long, low frequency, open class member of that Word 3 pair immediately following the position of Word 2. An example of a Word 2 pair (*winter/autumn*) in the two corresponding sentence frames with the Word 3 pair (*to/cold*) is shown in Table 1.

Two lists of materials were created. In the first list, one of the two members of a Word 2 pair was placed in one of the two sentence frames for that pair, while the other member was placed in the second frame. In the second list, the words in a Word 2 pair were swapped across the sentence frames for that pair. Thus, both members of each Word 2 pair were used in each list, but in a different sentence frame and therefore with a different Word 3. In each list, half of the closed-class members of a Word 3 pair appeared with a high frequency Word 2, and half appeared with a low frequency Word 2. Similarly, half of the open-class members of a Word 3 pair appeared with a high frequency Word 2, and half with a low frequency Word 2. Across lists, both members of each Word 2 pair appeared with both levels of Word 3 class. Each list contained 72 test sentences, the 2 members of each Word 2 pair in 36 pairs of sentence frames.

Procedure

The subject was seated in a comfortable chair and was supported by a chin and forehead rest to minimize body and head movements. At the beginning of the experiment, the eye tracking system was calibrated, a procedure that took under 5 minutes. At the beginning of the session, the subject read several practice sentences until he or she was familiar with the procedure. After the practice sentences, the subject read 72 test sentences. The order of sentence presentation was randomized for each subject.

A trial consisted of the following events: First, the experimenter checked the calibration accuracy of the eye movement system by displaying three check-points (at the beginning, middle, and end of the line on which sentences would appear) and a fourth point that indicated where the system estimated the current fixation position to be. The subject was asked to fixate each check-point, and if the estimated fixation position was within one character position of each check-point, calibration was determined to be accurate. The system was recalibrated whenever the calibration was not accurate by this definition. Second, the subject was asked to fixate a cross on the left side of the CRT when he or she was ready for a sentence. When the subject was ready, a single sentence was presented. The sentence always fit on one horizontal line across the CRT. The subject read each sentence and then pressed a button once it was understood. The button press caused the sentence to disappear and the calibration display to reappear. Subjects were asked a simple yes/no comprehension question at this time on 20% of the trials. Subjects were virtually flawless answering these questions. The entire experimental session lasted for about one hour.

Data Analysis

In the following analyses, the location of a word was defined as beginning at the space immediately to the left of the word and ending at the last letter of the word. Several measures of eye movement behaviour on Words 1, 2, and

3 were analyzed. Four of these measures reflect processing during the initial pass through the sentence: (a) Probability of first-pass fixation: the probability that the eyes landed within the word during the initial pass through the sentence, i.e., excluding fixations following a backward (regressive) eye movement; (b) Gaze duration: the amount of time spent within a word during the initial pass through the sentence, prior to moving off of that word the first time, i.e., total time from initially landing to initially leaving a word but excluding fixations following regressive saccades back to the word[1]; (c) Number of gaze fixations: the number of fixations whose durations are added together to produce the gaze duration; (d) Landing position: the character position on which the initial forward saccade lands. The gaze duration, number of gaze fixations, and landing position measures are contingent on the word being fixated. Because these four measures are assumed to reflect the initial processing of a word, the prediction derived from the parallel allocation hypothesis was that an effect of word $n + 1$ should be observed during fixation on word n, while the sequential allocation hypothesis predicted that no such effect of word $n + 1$ should be observed during fixation on word n.

Three additional measures reflected re-processing time on a word during subsequent passes through the sentence: (e) Percentage of regressions in: The percentage of times that a regressive saccade brought the eyes back to a word from a later point in the sentence; (f) Regressive fixation duration: the amount of time spent on a word following a regression back to that word (with non-regression times scored as zeros); (g) Total reading time: all time spent fixating a word, including refixations back to the word. Because these three measures reflect later processing on a word (following fixations on words that are later in the sentence), they would be expected to show effects of these later words. Such effects would constitute evidence that the manipulations of these later words were successful. For example, the sequential allocation hypothesis would predict no effect of word $n + 1$ on word n initial processing (i.e., before $n + 1$ is fixated), while the parallel allocation hypothesis would predict such an effect. However, an effect of word $n + 1$ on later processing of word n (i.e., after word $n + 1$ has been fixated) could be accommodated by either hypothesis, and would suggest that the manipulation of $n + 1$ had been successful.

Because reporting all of the means from such a large number of regions and measures can be overwhelming, we will concentrate on those effects that were statistically significant. Effects not mentioned had p values greater than .10.

1 We also analyzed first fixation durations, defined as the duration of the initial fixation on a word and exclusive of intra-word refixations. The results of this analysis were virtually identical to the gaze duration results. We have chosen to report the gaze durations because this measure offers a more extreme test of the sequential allocation hypothesis.

TABLE 2
Initial processing on Word 1 and Word 2, as a function of the difficulty of the next word (Word N + 1)

	Word N + 1	
Word 1	Easy	Difficult
Probability of Fixation	.67	.69
Gaze Duration	252	244
Number of Gaze Fixations	1.02	1.00
Landing Position	1.8	1.7
Word 2	Easy	Difficult
Probability of Fixation	.81	.84
Gaze Duration	252	244
Number of Gaze Fixations	1.28	1.36
Landing Position	2.2	2.3

RESULTS AND DISCUSSION

The following analyses excluded trials on which the eyetracker lost track of the eye position. About 1% of the trials were lost in total, and lost trials were randomly distributed across conditions.

Word 1, initial processing. Table 2 summarizes the initial processing measures on Word 1 as a function of the difficulty of Word 2. The mean probability of fixating Word 1 was .68, and was not affected by the difficulty of Word 2, $F < 1$. The mean gaze duration on Word 1 was 248 ms. Importantly, the gaze duration on Word 1 did not increase when Word 2 was more difficult. In fact, gaze durations on Word 1 were 8 ms longer when Word 2 was easier, though this effect was not significant, $F(1,23) = 1.34$, $MS_e = 997$, $p > .25$. The mean number of gaze fixations on Word 1 was 1.01, and also was not affected by the difficulty of Word 2, $F < 1$. The mean landing position was 1.8 characters into the word, and was not affected by the difficulty of Word 2, $F < 1$.

The initial processing data from Word 1 suggest that the difficulty of the next (parafoveal) word does not influence eye movement behaviour during the initial processing of the currently fixated word. This finding offers initial support for a model in which attention is sequentially allocated to the fixated and then the parafoveal word, rather than allocated to both in parallel.

Word 1, re-processing. Table 3 presents re-processing time on Word 1 as a function of Word 2 and Word 3 difficulty. Overall, regressions to Word 1 occurred 12% of the time, and were not affected by either the difficulty of Words 2 or 3, $F<1$ and $F(1,23) = 2.08$, $MS_e = 108$, $p > .15$, respectively. However, the amount of regressive fixation time spent on Word 1 was affected by the difficulty of both Word 2 and Word 3. Regressive fixation

TABLE 3
Re-processing on Word 1 as a function of the difficulty of both the next two words (Word N + 1 and Word N + 2)

Word 1	Word N + 1	
	Easy	Difficult
Percentage Regressions In	11	13
Regressive Fixation Duration	89	115
Total Time	359	397
Word 1	**Word N + 2**	
	Easy	Difficult
Percentage Regressions In	12	13
Regressive Fixation Duration	91	112
Total Time	362	395

duration on Word 1 was 26 ms longer when Word 2 was low vs high frequency (115 vs 89 ms), $F(1,23) = 10.5$, $MS_e = 1524$, $p < .005$, and 21 ms longer when Word 3 was a long, low frequency, open class word compared with a short, high frequency, closed class word (112 vs 91 ms), $F(1,23) = 18.7$, $MS_e = 554$, $p < .001$. Similarly, the total time spent on Word 1 was affected by the difficulty of Words 2 and 3. Total time was 38 ms longer when Word 2 was low versus high frequency (397 vs 359 ms), $F(1,23) = 6.13$, $MS_e = 5596$, $p < .05$, and 33 ms longer when Word 3 was a long, low frequency, open class word compared with a short, high frequency, closed class word (395 vs 362 ms), $F(1,23) = 8.50$, $p < .01$, $MS_e = 3185$.

Both the regressive fixation duration and the total reading time on Word 1 give a first indication that our manipulation of Word 2 and Word 3 difficulty was successful: Re-processing time on Word 1 was increased when Words 2 and 3 were more difficult. It therefore appears that the failure to find an effect of Word 2 on Word 1 initial processing measures cannot be explained by an inadequate manipulation of Word 2 difficulty.

Word 2, initial processing. Table 2 presents the initial processing measures on Word 2 as a function of Word 3 difficulty. The mean probability of fixating Word 2 was .82 and was not affected by the difficulty of Word 2 or Word 3 (all p's > .10). Gaze duration on Word 2 was not affected by the difficulty of Word 3, nor was there an interaction between Word 2 and Word 3 difficulty, F's < 1. Similarly, there was no effect of the difficulty of Word 3 on the number of gaze fixations on Word 2, and no interaction, p's > .15.

Table 4 shows the initial processing measures on Word 2 as a function of Word 2 difficulty. Gaze durations were 28 ms faster when Word 2 was high frequency compared with low frequency (247 vs 275 ms), $F(1,23) = 13.2$, $MS_e = 1468$, $p < .005$. The frequency of Word 2 also affected the number of gaze fixations on that word. High frequency words received .2 fewer gaze

TABLE 4
Initial processing on Word 2 and Word 3, as a function of the difficulty of that word (Word N)

	Word N	
Word 2	Easy	Difficult
Probability of Fixation	.82	.83
Gaze Duration	247	275
Number of Gaze Fixations	1.25	1.39
Landing Position	2.3	2.2
Word 3	Easy	Difficult
Probability of Fixation	.61	.83
Gaze Duration	212	266
Number of Gaze Fixations	.79	1.32
Landing Position	1.7	1.7

fixations than low frequency words (1.2 vs 1.4), $F(1,23) = 6.62$, $MS_e = .0728$, $p < .05$. Finally, the mean landing position within word 2 was 2.2 characters, and was not affected by the difficulty of Word 2 or Word 3, all F's < 1.

These eye movement data support several conclusions. First, the lack of any significant effects of the parafoveal word (Word 3) on initial processing of the currently fixated word (Word 2), in combination with similar findings from Word 1, strongly suggests that the difficulty of a parafoveal word does not affect the duration of the fixation on the current foveal word. Second, these data show that our manipulation of foveal load was successful: Words that had a lower frequency of occurrence were more difficult to process and were therefore fixated more and for a greater amount of time during the first pass through the sentence. Again, this finding makes it difficult to argue that the lack of an effect of Word 2 on the initial processing measures on Word 1 was due to an inadequate manipulation of Word 2 difficulty.

Word 2, re-processing. Table 5 presents re-processing time on Word 2 as a function of Word 2 and Word 3 difficulty. Overall, regressions to Word 2 occurred 13% of the time. There was some tendency for readers to execute more regressions back to a low frequency word compared with a high frequency word (14% vs 11%), but this tendency did not reach significance ($p > .10$). The regressive fixation duration on Word 2 showed a significant effect of the frequency of that word. Subjects spent 44 ms more fixated on a low frequency word following regressions than they did on a high frequency word (141 vs 97 ms, respectively), $F(1,23) = 7.30$, $p < .05$, $MS_e = 6190$. Finally, total reading time on Word 2 was 80 ms longer when it was a low frequency compared with a high frequency word (440 vs 360 ms), $F(1,23) = 15.1$, $MS_e = 10174$, $p < .005$

TABLE 5
Re-processing on Word 2 as a function of the difficulty of both that word (Word N) and the next word (Word + 1)

Word 2	Word N	
	Easy	Difficult
Percentage Regressions In	11	14
Regressive Fixation Duration	97	141
Total Time	360	440

Word 2	Word N + 1	
	Easy	Difficult
Percentage Regressions In	13	13
Regressive Fixation Duration	120	118
Total Time	394	406

In summary, the re-processing time measures on Word 2 clearly show that the low frequency words were more difficult to process than the high frequency words. Further, the finding that such a difference increased from 28 ms in the gaze duration data to 80 ms in the total time data suggests that at least part of the frequency effect occurs at stages of processing beyond word recognition, such as semantic integration.

Word 3, initial processing. Table 4 presents the initial processing measures on Word 3 as a function of Word 3 difficulty. As expected, there was a main effect of the lexical class of Word 3 on the mean probability that it would be fixated, with short, high frequency, closed class words fixated 22% less often than long, low frequency, open class words, $F(1,23) = 65.7$, $MS_e = 174$, $p < .001$. The long, low frequency, open class words were fixated 83% of the time, while the easier short, high frequency, closed class words were fixated only 61% of the time. There was no effect of the lexical frequency of Word 2 on the percentage of times Word 3 was fixated, $F < 1$, nor did the frequency of Word 2 interact with the difficulty of Word 3, $F(1,23) = 1.17$.

The gaze measures on Word 3 followed the same pattern as the probability of fixation data (see Table 4). First, for mean gaze duration, there was a main effect of the difficulty of Word 3, with gaze durations on short, high frequency, closed class words 54 ms shorter than on long, low frequency, open class words (212 vs 266 ms), $F(1,23) = 35.9$, $MS_e = 1903$, $p < .001$. There was no effect of the frequency of Word 2 on the gaze duration on Word 3, $F(1,23) = 1.36$, $MS_e = 1903$, $p > .25$, and no interaction between Word 2 and Word 3 difficulty, $F(1,23) = 1.06$, $MS_e = 1718$, $p > .30$. Similarly, for the number of gaze fixations there was a significant effect of difficulty, with .54 fewer fixations made on short, high frequency, closed class compared with long, low frequency, open class words (.79 vs 1.32 fixations), $F(1,23) = 112$, $MS_e = .0614$, $p < .001$. Again, there was no effect of the frequency of Word

2, and no interaction, both F's < 1. Finally, there was a significant effect of the difficulty of Word 3 on the initial landing position within the word. Mean landing position was .6 character spaces greater into a long, low frequency, open class compared with a short, high frequency, closed class word (2.3 vs 1.7 characters), $F(1,23) = 33.5$, $MS_e = .3128$, $p < .001$. This effect reflects the fact that a longer saccade would be more likely to miss a shorter word. There was no effect of the frequency of Word 2 on this measure, and no interaction, F's < 1.

The data from the eye movement behaviour on Word 3 support several conclusions. First, short, high frequency, closed class words are skipped more often than are longer, lower frequency, open class words. These data replicate the results reported in earlier correlational studies. In fact, our absolute rates of fixation are very close to those reported by Just and Carpenter (1987) for open and closed class words. Second, the time spent on a short, high frequency, closed class word, given that it was fixated, was less than the time spent on a long, low frequency, open class word, as shown by the shorter gaze durations. Thus, short, high frequency, closed class words are more likely to be skipped, and when they are fixated, they are fixated for less time. Third, there was no effect of Word 2 on any of the initial processing measures on Word 3. Thus, these data suggest that so-called "spillover" effects, in which processing difficulty in one region of a sentence is observed on the initial processing measures of later words (e.g., Ehrlich & Rayner, 1983), are not ubiquitous. At this point, it is not clear when spillover effects will and will not be observed.

Word 3, re-processing. Table 6 presents Word 3 re-processing as a function of Word 2 and Word 3 difficulty. There was a marginal tendency for subjects to regress to a long, low frequency, closed class word more often than to an short, high frequency, open class word (15% vs 12%), $F(1,23) = 3.17$, $MS_e = 74.9$, $p < .10$, but the amount of regressive fixation time spent on the former was 35 ms less than on the latter words (78 vs 113 ms), $F(1,23) = 22.7$, $MS_e = 1292$, $p < .001$. There was a significant interaction of the difficulty of Word 2 and 3 on the regressive fixation duration data on Word 3, $F(1,23) = 4.31$, $MS_e = 1400$, $p < .05$. Refixation time on short, high frequency, closed class words was 26 ms greater when they followed low frequency words compared with high frequency words (91 vs 65 ms); refixation time on long, low frequency, open class words differed by only 6 ms (in the opposite direction) as a function of the frequency of the previous word (110 vs 116 ms).

The total time spent on Word 3 was affected by both the frequency of Word 2 and the class of Word 3. Total time was 33 ms greater when Word 3 followed a low frequency word compared with a high frequency word (361 vs 328 ms), $F(1,23) = 5.51$, $MS_e = 4686$, $p < .05$, and was 114 ms greater when Word 3 was long, low frequency, and open class rather than short, high

TABLE 6
Re-processing on Word 3 as a function of the difficulty of the prior word (Words N − 1) and that word (Word N)

Word 3	Word N-1	
	Easy	Difficult
Percentage Regressions In	14	13
Regressive Fixation Duration	91	101
Total Time	328	361

Word 3	Word N	
	Easy	Difficult
Percentage Regressions In	15	12
Regressive Fixation Duration	78	113
Total Time	288	402

frequency, and closed class (402 vs 288 ms), $F(1,23) = 67.9$, $MS_e = 4570$, $p < .001$.

In summary, the re-processing time measures on Word 3 further support the adequacy of our manipulation of difficulty for Word 3. There was a tendency for subjects to regress more, spend more time following a regression, and spend more total time on a long, low frequency, open class word compared with a short, high frequency, closed class word. One interesting aspect of these data was the interaction between the frequency of Word 2 and the class of Word 3 on the regressive fixation data. This interaction can be thought of as a complicated type of spillover effect, where processing difficulty on a previous region is observed on *re-processing* time measures on a later region, but only when that later region is itself relatively easy. Given that we did not control the remainder of the sentence following Word 3, it is possible that the effect in our case was due to differences in the difficulty of integrating the remainder of the sentence with the earlier part of the sentence.

General Discussion

The main purpose of the present experiment was to determine whether the difficulty of the parafoveal word to the right of the currently fixated word during reading would affect eye movement behaviour on the current word. This issue is important because it directly bears on two hypotheses concerning the allocation of attention to words during reading. According to the *parallel attention hypothesis*, attention is simultaneously allocated to the currently fixated word and the next, parafoveal word. According to the *sequential attention hypothesis*, on the other hand, attention is allocated first to the currently fixated word, and then to the next one or two words in a sequential manner. If the parallel attention hypothesis were correct, then we would expect that the difficulty of the parafoveal word to the right of the fixated word would affect eye movement behaviour on the fixated word. If the sequential attention hypothesis were correct, we would expect no effect of the upcoming word until that word was fixated.

To contrast the two hypotheses, we constructed sentence frames within which we could vary parafoveal difficulty, holding foveal difficulty constant. One manipulation of difficulty involved lexical frequency, and another involved a combination of syntactic class, lexical frequency, and length. The results from both manipulations were clear. While both types of difficulty produced robust effects on eye movement behaviour once the words were fixated, neither produced even a hint of an effect when the words were in the parafovea. Thus, our results provide strong evidence against the parallel attention hypothesis and instead offer support for the sequential attention hypothesis. It is important to underscore that while the difficulty of the upcoming parafoveal word did not influence processing on the current word, parafoveal information from the upcoming word was acquired during fixation on the present word. This can be seen in the present study by the fact that easy words were more likely to be skipped, and by many previous studies showing that parafoveal preview benefits are obtained from an upcoming parafoveal word (e.g., Henderson & Ferreira, 1990; Rayner, 1975). Our point here is that this parafoveal information acquisition occurs *after* processing of the current word is complete. That is, information is acquired from word *n* and word *n + 1* sequentially during fixation on word *n*.

A secondary issue addressed by this study involved factors that control word skipping in reading. Our data indicated that the short, high frequency, closed class words were fixated about 20% less often than the more difficult long, low frequency, open class words, even though the position in the sentence was controlled. It is important to note that it is still unclear which aspects of a lexical item control whether or not it will be skipped. It has been suggested that lexical class plays a major role in determining word skipping (e.g., Carpenter & Just, 1983; Hogaboam & McConkie, 1981; Just & Carpenter, 1980; O'Regan, 1979). In our study, about 18% of the open class words at Words 2 and 3 were skipped, suggesting that it is not only closed class words that are skipped. Further, lexical class in general is correlated with length and frequency, as it was in our study, so that any or all of these factors may have some influence. In an attempt to tease apart these factors, Stephen Hayduk recently conducted a study in our laboratory in which he contrasted open- and closed-class words of equal length and frequency with the word "the" in identical sentence frames (Hayduk, 1990). For example, consider the sentence frame *Tom told us to install {three/those/the} lights in the basement.* In this case, "three" is open-class, "those" is closed-class of the same length and frequency, while "the" is much higher in frequency and shorter. In this study, Hayduk found that the probability of skipping the open-and closed-class words was identical (27%), while the probability of skipping "the" was much higher, at 65%. These data suggest that it is frequency and/or length that determines whether a word is skipped, rather than the lexical class per se.

Another aspect of the skipping data worth noting is that the likelihood of skipping a word is markedly reduced when the word immediately before had been skipped. For example, overall, the Word 3 difficult words were skipped 17% of the time versus 39% of the time for the easier words. However, when the word immediately before had not been fixated, the values changed to 4% of the difficult words skipped versus 12% for the easy words $F(1,23) = 20.9$, $MS_e = .0067$, $p < .001$. Thus, it appears that the majority of skips occur when the previous word had been fixated, as we would expect if words are skipped only when they have been parafoveally processed from an earlier position in the text.

ATTENTION AND EYE MOVEMENT CONTROL REVISITED

In this section, we briefly outline our view of eye movement control in reading. First, we take as our starting point Morrison's (1984) parallel programming model, as outlined in the Introduction. The main feature of the parallel programming model is that overlapping motor programs can sometimes exist simultaneously (hence parallel programming). Because our focus has been on the sequential nature of attentional allocation during fixations rather than on parallel programming, we have called our version of the basic model the sequential attention model (Henderson, 1988; Henderson, 1992; Henderson et al., 1989; Henderson & Ferreira, 1990). Perhaps the best moniker would be the *sequential attention – parallel programming model.* In any case, we make the following basic assumptions: First, at the beginning of a fixation on a new stimulus, attention is allocated to that stimulus. In reading, the stimulus would generally be the currently fixated word, though the reader would presumably have some control over whether attention were directed at the word, letter, or even page level (McConkie & Zola, 1987). Second, attention is redirected to a new word when processing on the fixated word is completed. Given that factors at the lexical (Henderson & Ferreira, 1990; Just & Carpenter, 1980; Rayner and Duffy, 1986), syntactic (Ferreira & Henderson, 1990, 1993; Frazier & Rayner, 1982), and semantic (Ehrlich & Rayner, 1983) levels can all exert an influence on first-pass processing on a word, completion probably entails at least partial analysis of the fixated word at all of these levels. Third, the reallocation of attention coincides with the signal to generate an eye movement to the new word, and the word toward which the eyes are programmed is the word to which attention is directed. Whether this relationship is structurally necessary or functionally convenient is an empirical issue yet to be resolved, though our bias at the present time is toward the former view (see Henderson, 1992, and Klein et al., 1992, for discussion of this issue). Fourth, the allocation of attention to the new word gates higher-level analysis of that word. By higher-level analysis, we mean acquisition of information beyond that which can be obtained preattentively, such as simple features (e.g., Treisman, 1988). Fifth, a saccade brings the eyes to the attended word following the eye movement programming latency. This latency would include the time to compute the eye movement parameters plus the neural transmission time to the ocular muscles, probably no less than 100 ms, and probably closer to 150 ms. Sixth, the preview benefit derived from the parafoveal word is assumed to be a function of the latency between the shift of attention and the saccade to that word (as well as other factors such as the visual eccentricity of the word, its size, etc.)

While the above model can account for a great deal of eye movement behaviour in reading, and with slight modification, in scene viewing (Henderson, 1992), it does have some difficulty accounting for one recent finding; the parafoveal preview benefit is reduced when word *n* is more difficult (Henderson and Ferreira, 1990). One way to deal with this finding would be to assume that attention is normally allocated to both the foveal and parafoveal word, as described in the Introduction. However, given that we can find no effect of the parafoveal word on foveal word processing in the current study, this approach does not seem viable. The alternative is to maintain the sequential attention assumption, but to suggest that when foveal processing is difficult, computations on an eye movement program can begin prior to the shift of attention, so that the latency between the shift of attention and the movement of the eyes is reduced. This is essentially the view taken by Henderson & Ferreira (1990; Henderson, 1992), and by Pollatsek and Rayner (1990), though the particulars differ in the two cases. In our view, the eye movement system imposes a deadline on the amount of time it is willing to devote to a particular fixation during reading. If the deadline is reached, the system will begin to program an eye movement even though attention has not yet been reallocated away from the currently fixated word. In the extreme case, this will lead to a refixation on a new part of the fixated word, which should aid further analysis. However, if processing on the fixated word is subsequently finished and attention shifts to the next word, the latency between the attentional shift and the eye movement will be reduced, due to savings in programming time (Morrison, 1984). Because parafoveal preview benefit is assumed to be a function of this latency, and because the latency is reduced, the preview benefit will also be reduced.

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