Journal of Experimental Psychology:
Learning, Memory, and Cognition
1990, Vol. 16, No. 3, 417–429

Copyright 1990 by the American Psychological Association, Inc.
0278-7393/90/$00.75

Effects of Foveal Processing Difficulty on the Perceptual Span in Reading: Implications for Attention and Eye Movement Control

John M. Henderson and Fernanda Ferreira
University of Alberta, Edmonton, Alberta, Canada

Two experiments were conducted to examine the effects of foveal processing difficulty on the perceptual span in reading. Subjects read sentences while their eye movements were recorded. By changing the text contingent on the reader's current point of fixation, foveal processing difficulty and the availability of parafoveal word information were independently manipulated. In Experiment 1, foveal processing difficulty was manipulated by lexical frequency, and in Experiment 2 foveal difficulty was manipulated by syntactic complexity. In both experiments, less parafoveal information was acquired when processing in the fovea was difficult. We conclude that the perceptual span is variable and attentionally constrained. We also discuss the implications of the results for current models of the relation between covert visual–spatial attention and eye movement control in reading.

This document is copyrighted by the American Psychological Association or one of its allied publishers.
This article is intended solely for the personal use of the individual user and is not to be disseminated broadly.

During reading, the eyes cycle through a series of saccades and fixations. Saccades are rapid, ballistic movements of the eyes that serve to project new areas of the visual field onto the fovea. Fixations are the brief pauses between saccades (averaging about four per second during reading) when visual information is acquired. In this article we will be concerned with the *perceptual span* during reading, the region of the visual field from which useful information can be acquired during a given eye fixation.

Recent developments in eye movement monitoring have provided a technique for fine-grained analysis of the perceptual span during reading. Particularly illuminating have been studies that have manipulated the amount and type of information available to the reader on a moment-by-moment basis as a function of eye position. For example, McConkie and Rayner (1975) studied the perceptual span by systematically mutilating the text outside of a limited "window" region around the fovea. Research using this technique has provided evidence that the perceptual span during reading is asymmetric, extending from about 4 characters to the left of the character at the fixation point (McConkie & Rayner, 1976; Rayner, Well, & Pollatsek, 1980; Underwood & McConkie, 1985) to about 15 characters to the right (McConkie & Rayner, 1975; Rayner, Inhoff, Morrison, Slowiaczek, & Bertera, 1981).

The asymmetry of the perceptual span in reading is interesting because it suggests that attentional factors play a role in the acquisition of information during a fixation. Other paradigms also provide support for a link between attention and the perceptual span. For example, Rayner, McConkie, and Ehrlich (1978) presented subjects with two words, one to either side of the point of fixation. The subject's task was to move his or her eyes to one of the words and then to name that word as quickly as possible. During the eye movement, the two extrafoveal words were replaced on the screen so that the target word was the same in both locations. Rayner et al. found that an extrafoveal preview of a word in a location opposite to that in which the eyes were about to move provided no facilitation in naming latency over having an incorrect preview, whereas a preview in the location to which the eyes were about to move facilitated naming latency. The Rayner et al. (1978) results suggest that little information is acquired from an extrafoveal location which is in the opposite direction from that in which the eyes are about to move. In addition, the results indicate that useful information is acquired prior to the eye movement from the position to which the eyes are about to move.

One explanation for the asymmetry of the perceptual span observed in both the reading and naming studies is that a covert shift of attention precedes the eyes in the direction of the next eye movement (e.g., Bryden, 1961; Crovitz & Daves, 1962; Henderson, Pollatsek, & Rayner, 1989; Klein, 1980; McConkie, 1979; Morrison, 1984; Rayner, Murphy, Henderson, & Pollatsek, 1989; Remington, 1980; Shepherd, Findlay, & Hockey, 1986). Consistent with this hypothesis, Pollatsek,

---

Aspects of these data were presented at the 1987 Joseph R. Royce Research Conference, Edmonton, and the 1989 meeting of the Psychonomic Society, Atlanta. The research presented in this article was supported by operating grants from the Natural Sciences and Engineering Research Council of Canada to John Henderson (OGP-41792) and Fernanda Ferreira (OGP-37323), and by a Killam Postdoctoral Fellowship to John Henderson. The research was conducted at the University of Massachusetts and was partially supported by a grant from the National Science Foundation (BNS86-09336) to Keith Rayner and Alexander Pollatsek.

We would like to thank Sandy Pollatsek and Keith Rayner for many fruitful discussions of the issues raised in this article, and Albrecht Inhoff, David Irwin, David Zola, and an anonymous reviewer for their comments on an earlier version of the manuscript.

Correspondence concerning this article should be addressed to John M. Henderson at the Department of Psychology, P-220 Biological Sciences Building, University of Alberta, Edmonton, Alberta, Canada T6G 2E9. Electronic mail may be sent to JMHE@UALTAMTS.bitnet.

This document is copyrighted by the American Psychological Association or one of its allied publishers.
This article is intended solely for the personal use of the individual user and is not to be disseminated broadly.

Bolozky, Well, and Rayner (1981) found that the asymmetry of the perceptual span was leftward for readers fluent in both English and Hebrew when they were reading Hebrew, a language in which eye movements are primarily right to left. Similarly, Inhoff, Pollatsek, Posner, and Rayner (1989) found that when readers of English were required to read from right to left, the asymmetry of the perceptual span reversed so that readers acquired information primarily from the left side of the point of fixation. Finally, Henderson et al. (1989) presented subjects with an array of four objects arranged at the corners of an imaginary square and manipulated the location(s) at which extrafoveal information was available. Again, extrafoveal information was primarily acquired only from the location to which the eyes were about to move.

The Inhoff et al. (1989) and Henderson et al. (1989) studies both provide evidence that the asymmetry of the perceptual span is not due to the effects of practice at reading in a particular direction. Instead, it appears that a general aspect of information acquisition during eye fixations is that extrafoveal information is acquired primarily from the position that is about to be fixated next. This point is made particularly salient by the Henderson et al. (1989) study because eye movement direction changed as each object was fixated during a trial.

Foveal Difficulty and the Perceptual Span

Given that spatial attention has been implicated in the acquisition of extrafoveal information, the question arises whether attention is shared among the foveal and extrafoveal locations or whether it is sequentially allocated to the two locations. If there is competition between foveal and extrafoveal stimuli for attentional resources, then one might expect that foveal processing difficulty would decrease the resources available for extrafoveal processing, thereby reducing the effective perceptual span. Research employing tachistoscopic presentation of simple visual displays has tended to support this idea (Holmes, Cohen, Haith, & Morrison, 1977; Ikeda & Takeuchi, 1975; Mackworth, 1965; Williams, 1982, 1985). However, because these studies did not allow subjects to move their eyes during the course of the task, it is not clear whether the results would generalize to a viewing situation like skilled reading in which eye movements are an essential component.

There is some evidence that the perceptual span during reading may vary with foveal processing difficulty (Inhoff et al., 1989; Rayner, 1986). Rayner (1986) used the moving window technique to explore the size of the perceptual span in beginning and skilled readers and found that the perceptual span of beginning readers was approximately 20% smaller than that of skilled readers. Further, the size of the perceptual span varied as a function of the difficulty of the text being read—namely, less information was acquired when the text was more difficult. Rayner proposed that the perceptual span varies as a function of foveal processing difficulty. According to this hypothesis, the perceptual span of beginning readers is reduced because beginning readers use a greater proportion of total processing resources for decoding the fixated word than do skilled readers, and therefore have fewer resources left over for acquiring extrafoveal information. The reduced perceptual span found with difficult texts can similarly be accounted for by assuming that on average, foveal processing is more difficult and therefore requires more processing resources when the text is difficult. This view leads to the somewhat counterintuitive prediction that increased foveal difficulty causes a longer fixation duration together with decreased extrafoveal information acquisition during that fixation.

The results reported by Rayner (1986) seem to indicate that foveal processing difficulty affects the perceptual span. However, there is a potential problem with interpreting the Rayner study: Both the reading skill and text difficulty manipulations covaried foveal *and extrafoveal* processing difficulty. Therefore, the decreased perceptual span could be due either to increased foveal processing difficulty or more directly to increased extrafoveal processing difficulty. It has been shown that extrafoveal information use during reading is affected by at least two factors: the predictability of the parafoveal word (Balota, Pollatsek, & Rayner, 1985; Balota & Rayner, 1983; McClelland & O'Regan, 1981) and the frequency of the parafoveal word (Inhoff & Rayner, 1986).

The purpose of the present study was to unconfound foveal and extrafoveal processing difficulty in order to determine whether foveal processing difficulty alone can influence the perceptual span during reading. We asked whether increasing the difficulty of the currently fixated (foveal) word would decrease the amount of information acquired from the next (parafoveal) word. In order to explore this question, we had subjects read sentences while their eye movements were recorded. By employing a paradigm in which the display was changed contingent on the position of the eyes (i.e., the *boundary technique*; Rayner, 1975), we independently manipulated the difficulty of the foveal word and the availability of parafoveal information. In order to examine the influence of foveal processing difficulty, two sets of sentences were constructed. In the first set, foveal difficulty was manipulated at the lexical level by means of word frequency. In the second set, foveal difficulty was manipulated at the syntactic level by means of syntactic complexity. Both sets of materials were presented intermixed to each subject. However, for expository purposes, we will present the data based on these sets of materials as Experiment 1 (lexical manipulation) and Experiment 2 (syntactic manipulation). Parafoveal information was manipulated by providing a preview of the parafoveal word that was either visually similar or visually dissimilar to the word that occupied the parafoveal location once that location was fixated. In this way, the influence of the difficulty of the foveal word on the perceptual span was examined independently of the difficulty of the parafoveal word.

Experiment 1

The primary question explored in Experiment 1 was whether a manipulation that increased foveal processing difficulty would decrease the acquisition of information from the next word in the sentence. This question was addressed by examining the amount of benefit derived from a parafoveal preview of the parafoveal target as a function of the frequency of the foveal word.

Subjects read sentences like the example in Table 1. Two factors were manipulated within sentences: frequency of the

This document is copyrighted by the American Psychological Association or one of its allied publishers.
This article is intended solely for the personal use of the individual user and is not to be disseminated broadly.

Table 1
Example Sentence in Each of the Six Foveal Frequency × Parafoveal Preview Conditions: Experiment 1

H-F foveal word, same parafoveal preview
Mary bought a chest despite the high price.
Mary bought a chest despite the high price.
H-F foveal word, similar parafoveal preview
Mary bought a chest desqlda the high price.
Mary bought a chest despite the high price.
H-F foveal word, dissimilar parafoveal preview
Mary bought a chest zqdloyv the high price.
Mary bought a chest despite the high price.
L-F foveal word, same parafoveal preview
Mary bought a trunk despite the high price.
Mary bought a trunk despite the high price.
L-F foveal word, similar parafoveal preview
Mary bought a trunk desqlda the high price.
Mary bought a trunk despite the high price.
L-F foveal word, dissimilar parafoveal preview
Mary bought a trunk zqdloyv the high price.
Mary bought a trunk despite the high price.

Note. The pair of stimuli shown for each condition indicates the display prior to and following the eye's crossing of the display change boundary. For this example, *chest* (or *trunk*) was the foveal word, and *despite* was the parafoveal target. The boundary was placed prior to the letter *t* in *chest* or *k* in *trunk*. H-F = high frequency; L-F = low frequency.

foveal word and visual similarity of the parafoveal preview (the stimulus seen parafoveally prior to fixation on that location) to the parafoveal target (the word seen at that location once fixated). In the Table 1 example, *chest* served as the high-frequency foveal word, and *trunk* served as the low-frequency foveal word. Also as shown in Table 1, *despite* served as the parafoveal target, and the parafoveal preview was either identical to the parafoveal target (e.g., *despite*), visually similar to the parafoveal target (e.g., *desqlda*), or visually dissimilar to the parafoveal target (e.g., *zqdloyv*). Subjects read sentences such as the example in Table 1 while their eye movements were recorded. The eyetracker was interfaced with the display screen so that the parafoveal preview could be changed to the parafoveal target word during the saccade leading to the eye fixation on that word. Therefore, while the subject might be presented with a nonword parafoveally, the appropriate target word would be displayed when that position was fixated.

If the difficulty of the foveal word can reduce the acquisition of parafoveal word information, then there should be less parafoveal preview benefit (the difference between a similar and dissimilar parafoveal preview) when the foveal word has a low frequency than when it has a high frequency.

Method

Subjects. Twelve members of the University of Massachusetts community were paid $5 to participate in the experiment. The participants had been in previous eye movement experiments and were therefore familiar with the procedure. All participants had normal uncorrected vision and were not aware of the purpose of the experiment.

Apparatus. Eye movements were recorded by a Stanford Research Institute Dual Purkinje eyetracker with a resolution of about 10 min of arc. The eyetracker was interfaced with a Hewlett-Packard 2100 computer that controlled the experiment. Eye movements were recorded from the right eye, and viewing was binocular. The output of the eyetracker was linear over the visual angle subtended by the sentences. The signal from the eyetracker was sampled at a 1 kHz rate through an analog-to-digital converter, and every four samples were compared with the prior four samples in order to determine whether the eyes were stationary or in motion. The eyes had to be motionless for a minimum of 10 ms to be counted as a fixation. For further details of the apparatus, see Rayner, Well, Pollatsek, and Bertera (1982).

Sentences were presented on a Hewlett-Packard 1300A CRT in lower case, except for the first letter of each sentence and the first letter of proper nouns. All sentences were displayed on a single line. The luminance on the CRT was adjusted throughout the session in order to maintain a comfortable level of brightness for the subject. The subject's eyes were 46 cm from the CRT so that three characters equalled 1° of visual angle. The room was dimly illuminated by an indirect light source that allowed the experimenter to score responses to comprehension questions asked throughout the experiment.

Materials. The foveal words consisted of 36 pairs of words that varied in lexical frequency, as assessed with the Kučera and Francis (1967) norms. The mean frequencies were 148 and 12 counts per million for the high- and low-frequency nouns, respectively. The words in each pair were either synonyms or closely related words (e.g., *winter, autumn*) matched on word length. A complete list of the foveal words is given in the Appendix.

For each foveal word pair (e.g., *chest/trunk*), two sentence frames were constructed. Both foveal words from a pair formed a coherent sentence when entered into either frame. Two lists of materials were created. In the first list, one of the two foveal words from a pair was placed in one of the two sentence frames for that pair, while the other foveal word was placed in the second frame. In the second list, the foveal words in a pair were swapped across the sentence frames for that pair. Thus, both members of each foveal word pair were used in each list but in a different sentence frame. Each list contained 72 test sentences, the two foveal words from each pair in 36 pairs of sentence frames. Each list also contained 80 filler sentences which were the test stimuli for Experiment 2.

For each sentence frame, three parafoveal previews were created for the word immediately following the foveal word (the parafoveal target). The first parafoveal preview was identical to the parafoveal target (*same* condition), the second had the same first three letters and visually similar letters for the remainder (*similar* condition), and the third parafoveal preview consisted of letters visually dissimilar to the parafoveal target word (*dissimilar* condition). Visual similarity of letters was primarily based on differences between ascenders, descenders, and letters that do not extend above or below the line. When letters in the parafoveal target were replaced with visually similar letters in the parafoveal preview, ascenders replaced ascenders, descenders replaced descenders, and nonextenders were replaced by nonextenders. For visually dissimilar parafoveal previews, a letter was always replaced by a letter of a different type. Thus, in the similar condition, both the identity of the first three letters and the word shape of the parafoveal target were preserved, while in the dissimilar condition, neither letter identities nor word shape were preserved.[1] Table 1 presents an example sentence along with the foveal words, parafoveal previews, and parafoveal target for that sentence.

---

[1] In some sentences, the foveal word was followed by a short function word and a content word (e.g., *to fight*). For these sentences, the parafoveal target was defined as both words, and the parafoveal previews were defined in terms of the entire region (e.g., same: *to fight*; similar: *to flpdb*; dissimilar: *sy paogs*). No differences were found for these two-word preview regions in comparison to the single-word previews.

This document is copyrighted by the American Psychological Association or one of its allied publishers.
This article is intended solely for the personal use of the individual user and is not to be disseminated broadly.

A Latin-square design was employed so that each subject saw an equal number of sentences in each combination of foveal target and parafoveal preview conditions, while across subjects each sentence was seen in each condition by an equal number of subjects.

Procedure. When a subject arrived for the experiment, a bite bar was prepared and used to minimize the subject's head movements. The eye tracking system was then calibrated, a procedure that took about 10 min. At the beginning of the session, the subject read 10 practice sentences. After the practice sentences, the subject read 152 sentences. Seventy-two of these were the stimuli for Experiment 1, and the other 80 were the stimuli for Experiment 2. The order of sentence presentation was randomized for each subject.

In order to effect the display change from the parafoveal preview to the parafoveal target, a software-defined boundary (invisible to the subject) was placed between the penultimate and final letters of the foveal word. As soon as the eyetracker detected that the eye position had crossed this boundary, the computer replaced the parafoveal preview with the parafoveal target. This change was accomplished in less than 5 ms and therefore generally took place while the eye was moving. For this reason, the subjects were not consciously aware that display changes were taking place (see also Balota et al., 1985; Rayner, 1975). Those few trials on which a subject did see a change take place were discarded.

A trial consisted of the following events: First, the experimenter checked the calibration of the eye movement system, and the system was recalibrated when necessary. Second, the subject was asked to fixate a cross on the left side of the cathode-ray tube (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. Because subjects were virtually flawless in answering these questions, they were not scored. The experiment lasted for about 1 hr.

Results

The following analyses excluded trials on which the eyetracker lost track of the eye position, the foveal word or parafoveal target was not fixated, the first fixation on the foveal word was on the last letter of that word (i.e., the first fixation on the foveal word was past the boundary used to trigger the display change), the subject saw the display change take place, or the fixation duration was greater than 3 standard deviations from the mean for that subject in that condition. About 7% of the trials were lost in total, and lost trials were approximately equally distributed across conditions.

Mean first fixation durations (time spent on the word immediately after the eyes landed on it and excluding any additional fixations within the word) and mean gaze durations (total time spent on the word prior to moving off of it) were computed for the foveal words and the parafoveal targets given that they were fixated. Analyses of variance (ANOVAS) were conducted in which both subjects (F_1) and items (F_2) were treated as random effects.

Table 2 presents the mean first fixation durations and mean gaze durations on the foveal word as a function of condition. For the first fixation duration data, the 6-ms effect of lexical frequency on the foveal word (220 vs. 226 ms for the high- and low-frequency foveal words) was not significant, $F_1(1, 11) = 1.28$, $MS_e = 4{,}164$, $p > .25$, $F_2(1, 71) = 3.72$, $MS_e = 7{,}992$, $p < .10$. Neither the effect of parafoveal preview nor the interaction of preview and lexical frequency approached significance (all $Fs < 1$). Lexical frequency did, however, have an effect on the gaze durations. High-frequency foveal words were fixated for an average of 28 ms less than were low-frequency words (239 vs. 267 ms respectively), $F_1(1, 11) = 6.02$, $MS_e = 3{,}957$, $p < .05$, $F_2(1, 71) = 8.21$, $MS_e = 6{,}507$, $p < .01$. No other effects on the foveal word were significant (all $Fs < 1$).

Table 3 presents mean first fixation and gaze durations on the parafoveal target words as a function of condition. For the first fixation duration data, neither the effect of foveal frequency nor the effect of parafoveal preview was significant ($Fs < 1$). The interaction of Foveal Frequency × Parafoveal Preview was, however, significant, $F_1(2, 22) = 5.60$, $MS_e = 7{,}328$, $p < .05$, $F_2(2, 142) = 7.21$, $MS_e = 7{,}105$, $p < .001$. When the foveal word was a low-frequency word, the parafoveal preview benefit for the same preview versus dissimilar preview was -3 ms, and the preview benefit for the similar versus dissimilar preview was -4 ms. However, when the foveal word was a high-frequency word, the preview benefit was 10 ms for both the same and similar previews versus the dissimilar preview. The pattern observed in the gaze duration data was similar to the first fixation duration data, $Fs < 1$ for the main effects, $F_1(2, 22) = 3.27$, $MS_e = 8{,}640$, $p < .10$, $F_2(2, 142) = 4.36$, $MS_e = 10{,}037$, $p < .05$, for the interaction of foveal frequency and parafoveal preview.

Table 2
Mean First Fixation Duration (FFD) and Gaze Duration (Gaze) on the Foveal Word (in Milliseconds) as a Function of Foveal Frequency and Parafoveal Preview: Experiment 1

	Preview							
Foveal frequency	Same		Similar		Dissimilar		Mean	
	FFD	Gaze	FFD	Gaze	FFD	Gaze	FFD	Gaze
High	227	243	222	228	211	246	220	239
Low	226	266	227	265	225	270	226	267
Mean	226	254	224	246	218	258		

Table 3
Mean First Fixation Duration (FFD) and Gaze Duration (Gaze) on the Parafoveal Target (in Milliseconds) as a Function of Foveal Frequency and Parafoveal Preview: Experiment 1

	Preview							
	Same		Similar		Dissimilar		Mean	
Foveal frequency	FFD	Gaze	FFD	Gaze	FFD	Gaze	FFD	Gaze
High	227	248	227	241	237	261	230	250
Low	232	266	231	260	228	263	230	263
Mean	230	257	229	250	232	262	230	256

Discussion

Several aspects of the data reported in this experiment are consistent with earlier studies. First, lexical frequency affected the duration of a fixation on a word (e.g., Inhoff, 1984; Inhoff & Rayner, 1986; Just & Carpenter, 1980; Rayner & Duffy, 1986). Unlike many of these prior studies, the frequency effect that we observed was not reliable in the first fixation duration data, although the trend was in the right direction in the first fixation data, and the effect was significant in the gaze duration data. Second, in the foveal difficulty condition that produced a preview benefit (the high lexical frequency condition), a visually similar parafoveal preview that preserved general letter features and that contained the same first three letters as the parafoveal target was about as useful as a parafoveal preview that was identical to the parafoveal target (Balota et al., 1985; Inhoff, 1987; Lima, 1987; Rayner, 1975; Rayner, McConkie, & Zola, 1980; Rayner et al., 1982).

Most important, the data reported in this experiment support the view that during reading, the difficulty of the word currently under fixation affects the amount of information that can be acquired from the next (parafoveal) word. Specifically, we found that when the frequency of the word under fixation was relatively high, a parafoveal preview of the next word was more beneficial than when the frequency of the word under fixation was relatively low. This relation held even though the parafoveal word was potentially available for parafoveal processing for a greater amount of time when a low-frequency word was at the center of fixation than when a high-frequency was. An explanation for this effect will be explored in the General Discussion.

Experiment 2

Experiment 1 demonstrated that increasing the difficulty of foveal processing decreased the acquisition of parafoveal word information during reading. In Experiment 1, foveal difficulty was manipulated by word frequency. In some views, lexical frequency has its effect at the lexical access stage (e.g., Becker & Killion, 1977; Morton, 1969) rather than at higher levels such as the text integration stage (Rayner & Duffy, 1986). Therefore, it could be argued that foveal processing difficulty affected the acquisition of parafoveal word information because both foveal and parafoveal word processing competed for resources at the lexical level. If this is true, then not all types of foveal difficulty should affect acquisition of parafoveal word information. Experiment 2 served as a replication of Experiment 1 but with a syntactic manipulation of foveal processing difficulty. Syntactic difficulty was manipulated by maintaining or violating the reader's expectations concerning the attachment of a new constituent into the syntactic tree under construction. Sentences were employed containing a region that was temporarily structurally ambiguous between a sentence complement reading and a noun phrase reading. Previous research has shown that when the overt complementizer *that* is absent from such a sentence, and the sentence continues with the sentence complement attachment, processing difficulty and therefore fixation times increase on the word that disambiguates the structural ambiguity (Ferreira & Henderson, in press; Frazier & Rayner, 1982; Rayner & Frazier, 1987). If it is the case that foveal processing difficulty must be at the lexical level to affect parafoveal information acquisition, then the syntactic manipulation should not affect parafoveal information acquisition. If, on the other hand, foveal processing difficulty in general can affect parafoveal information acquisition, then the syntactic manipulation should produce a pattern of data similar to that found in Experiment 1.

Method

Subjects, apparatus, and procedure. Because Experiments 1 and 2 were conducted together, the subjects, apparatus, and procedure were identical to those described in Experiment 1.

Materials. The experimental materials consisted of sentences containing a region that was temporarily structurally ambiguous between a sentence complement reading and a noun phrase reading. All of the sentences eventually continued so that the sentence complement attachment proved to be correct. Two versions of each sentence were employed. One version contained the overt complementizer *that*, while the other version excluded the overt complementizer. The foveal word was defined as the word that disambiguated the structural ambiguity (given that the complementizer was absent). When the complementizer was present, the foveal word was considered easy, and when the complementizer was absent, the foveal word was considered difficult. The materials were divided into four lists.[2]

---

[2] Four lists were employed because the presence or absence of the overt complementizer was crossed with a second syntactic factor, verb subcategorization preference. However, because this factor did not produce an effect on either the foveal word or parafoveal target, it is irrelevant for the purposes of this article. More details can be found in Ferreira and Henderson (in press).

This document is copyrighted by the American Psychological Association or one of its allied publishers.
This article is intended solely for the personal use of the individual user and is not to be disseminated broadly.

This document is copyrighted by the American Psychological Association or one of its allied publishers.
This article is intended solely for the personal use of the individual user and is not to be disseminated broadly.

A single list consisted of 80 experimental sentences (plus the materials from Experiment 1), half of which contained the complementizer. A complete list of these materials can be found in Ferreira and Henderson (in press).

Parafoveal preview was manipulated by providing a preview that was either the same, visually similar, or visually dissimilar to the parafoveal target, as defined in Experiment 1. A Latin-square design was employed so that each subject saw an equal number of sentences in each combination of foveal target and parafoveal preview conditions, while across subjects each sentence was seen in each condition by an equal number of subjects. Table 4 presents an example sentence in the easy and difficult foveal conditions, along with the parafoveal previews and parafoveal target.

Results

The following analyses excluded trials on which the eyetracker lost track of the eye position, the foveal word or parafoveal target was not fixated, the first fixation on the foveal word was on the last letter of that word (i.e., the first fixation on the foveal word was past the boundary used to trigger the display change), the subject saw the display change take place, or the fixation duration was greater than 3 standard deviations from the mean for that subject in that condition. About 6% of the trials were lost in total, approximately equally distributed across conditions.

Table 5 presents the mean first fixation and gaze duration data on the foveal word as a function of condition.[3] For the first fixation duration data, the main effect of the syntactic manipulation was significant, $F_1(1, 11) = 8.41$, $MS_e = 3{,}912$, $p < .05$, $F_2(1, 79) = 9.00$, $MS_e = 7{,}251$, $p < .005$; that is, first fixation durations were shorter when the foveal word was syntactically easier (i.e., the complementizer was present). There was no main effect of parafoveal preview, nor did the two factors interact (all *F*s approximately 1).

For the gaze duration data, the pattern was similar, except that the effect of the syntactic manipulation did not reach significance, $F_1(1, 11) = 4.16$, $MS_e = 5{,}212$, $p < .05$, $F_2(1, 79) = 2.10$, $MS_e = 8{,}610$, $p > .05$. There was again no effect of parafoveal preview, and no interaction between the two factors (all *F*s approximately 1).

Table 6 presents the mean first fixation durations and mean gaze durations for the parafoveal target word as a function of foveal difficulty and parafoveal preview. For the first fixation duration data, there was no main effect of syntactic difficulty, $F_1(1, 11) = 2.65$, $MS_e = 10{,}375$, $p > .10$, $F_2(1, 79) = 1.09$, $MS_e = 8{,}416$, $p > .25$, nor was there a main effect of parafoveal preview (*F*s < 1). There was, however, a significant interaction of Syntactic Difficulty × Parafoveal Preview, $F_1(2, 22) = 5.25$, $MS_e = 9{,}591$, $p < .05$, $F_2(2, 142) = 6.42$, $MS_e = 10{,}480$, $p < .005$. When the foveal word was syntactically difficult, the parafoveal preview benefit for the same preview versus dissimilar preview was −8 ms, and the preview benefit for the similar versus dissimilar preview was −6 ms. When the foveal word was syntactically easier, the preview benefit was 39 ms for the same preview versus the dissimilar preview and 35 ms for the similar preview versus the dissimilar preview.

The pattern observed in the gaze duration data was similar to the first fixation duration data. There were no main effects of syntactic difficulty or parafoveal preview (all *F*s approximately 1). The interaction between syntactic difficulty and parafoveal preview evident in Table 6 was significant, $F_1(2, 22) = 6.14$, $MS_e = 9{,}298$, $p < .01$, $F_2(2, 142) = 8.55$, $MS_e = 6{,}527$, $p < .001$. When the foveal word was syntactically difficult, the preview benefit for the same and similar previews compared with the dissimilar preview was −4 and −3 ms. When the foveal word was syntactically easy, the corresponding preview benefits were 26 and 23 ms.

Discussion

The results of Experiment 2 replicated the results observed in Experiment 1. First, as reported in Ferreira and Henderson (in press), foveal processing difficulty generated by syntactic garden path sentences affected the duration of the first fixation on the syntactically disambiguating word (Ferreira & Clifton, 1986; Frazier & Rayner, 1982; Rayner, Carlson, & Frazier, 1983; Rayner & Frazier, 1987) and also tended to influence gaze duration on the word. Second, given that a preview benefit was found (i.e., the foveally easy condition), once again a visually similar parafoveal preview that contained the same first three letters and preserved the overall word shape of the parafoveal target was as beneficial as a preview identical to the parafoveal target.

The most important finding of this experiment was that the foveal processing difficulty produced by a syntactic manipulation influenced parafoveal information use in a manner similar to that observed with the lexical manipulation of Experiment 1. These data suggest that the reduced preview benefit found when foveal processing is difficult is not due to competition at the lexical level.

Table 4
Example Sentence in Each of the Six Foveal Syntactic Difficulty × Parafoveal Preview Conditions: Experiment 2

Syn. easy foveal word, same parafoveal preview
She warned that Harry bought small gifts.
She warned that Harry bought small gifts.
Syn. easy foveal word, similar parafoveal preview
She warned that Harry bought smadd gifts.
She warned that Harry bought small gifts.
Syn. easy foveal word, dissimilar parafoveal preview
She warned that Harry bought tipoa gifts.
She warned that Harry bought small gifts.
Syn. difficult foveal word, same parafoveal preview
She warned Harry bought small gifts.
She warned Harry bought small gifts.
Syn. difficult foveal word, similar parafoveal preview
She warned Harry bought smadd gifts.
She warned Harry bought small gifts.
Syn. difficult foveal word, dissimilar parafoveal preview
She warned Harry bought tipoa gifts.
She warned Harry bought small gifts.

Note. The pair of stimuli shown for each condition indicates the display prior to and following the eye's crossing of the display change boundary. For this example, *bought* was the foveal word, and *small* was the parafoveal target. The boundary was placed prior to the letter *t* in *bought*. Syn. = syntactically.

---

[3] These data have been partially reported by Ferreira and Henderson (in press) but are presented here again for the sake of clarity.

Table 5
Mean First Fixation Duration (FFD) and Gaze Duration (Gaze) on the Foveal Word (in Milliseconds) as a Function of Foveal Syntactic Difficulty and Parafoveal Preview: Experiment 2

Foveal difficulty	Preview: Same FFD	Same Gaze	Similar FFD	Similar Gaze	Dissimilar FFD	Dissimilar Gaze	Mean FFD	Mean Gaze
Easy	200	219	205	228	198	228	201	225
Difficult	230	253	210	242	229	258	223	251
Mean	215	236	208	235	214	243	212	238

An interesting aspect of the data found in both Experiments 1 and 2 was the tendency for the dissimilar preview conditions to lead to longer fixation durations on the target when the foveal word was easy compared with when it was difficult. In Experiment 1, this pattern can be seen in the first fixation duration data (Table 3), and in Experiment 2, in both the first fixation and gaze duration data (Table 6). This pattern indicates that when foveal processing is difficult, little or no information is acquired from any of the preview conditions (identical, similar, or dissimilar). On the other hand, when foveal processing is easy, information is acquired from all preview conditions. The information acquired in the identical and similar conditions leads to facilitated processing (hence, the generally shorter fixation durations compared with the dissimilar conditions). The information acquired in the dissimilar condition leads to slower processing due to an incompatibility between the information acquired parafoveally with that acquired foveally (hence, leading to the longer fixation durations in the easy-dissimilar versus difficult-dissimilar conditions). This pattern, then, is consistent with the general notion that the amount of parafoveal information acquired decreases when foveal processing difficulty increases.

General Discussion

In this study we examined the effects of foveal processing difficulty on the acquisition of parafoveal word information. In order to explore this issue, we independently manipulated the difficulty of the foveal word and the amount of information available from the parafoveal word. In Experiment 1, we found that if a low-frequency word was fixated, less information was acquired from the parafoveal word than if a high-frequency word was fixated. In Experiment 2, we found that when a word was fixated that violated the syntactic parser's expectations, less information was acquired from a parafoveal word than when a word was fixated that was consistent with syntactic expectations. In both experiments, less information was acquired from the parafoveal word when foveal processing was more difficult, despite the fact that in the difficult conditions the parafoveal word was available for a longer amount of time than in the easy conditions.

The results of these experiments have three general implications. First, they suggest that the perceptual span for a given reader does not consist of a constant amount of text from fixation to fixation. Instead, it appears that the perceptual span in reading varies across fixations and depends both on the difficulty of the parafoveal information (e.g., Balota et al., 1985; Inhoff & Rayner, 1986) and the difficulty of the foveal word currently being processed. This finding is consistent with the hypothesis advanced by Rayner (1986) that the perceptual span of beginning readers is smaller than that of skilled readers because beginning readers have more difficulty processing the foveal word. In addition, because the perceptual span was found to be variable, the results are consistent with the notion that estimates of the size of the perceptual span reported in previous studies using the moving window paradigm (e.g., DenBuurman, Boersema, & Gerrisen, 1981; McConkie & Rayner, 1975; Rayner & Bertera, 1979) were actually estimates of the maximum size of the perceptual

This document is copyrighted by the American Psychological Association or one of its allied publishers.
This article is intended solely for the personal use of the individual user and is not to be disseminated broadly.

Table 6
Mean First Fixation Duration (FFD) and Gaze Duration (Gaze) on the Parafoveal Target (in Milliseconds) as a Function of Foveal Syntactic Difficulty and Parafoveal Preview: Experiment 2

Foveal difficulty	Preview: Same FFD	Same Gaze	Similar FFD	Similar Gaze	Dissimilar FFD	Dissimilar Gaze	Mean FFD	Mean Gaze
Easy	281	335	285	338	320	361	296	345
Difficult	317	351	315	350	309	347	314	349
Mean	299	343	300	344	314	354	305	347

This document is copyrighted by the American Psychological Association or one of its allied publishers.
This article is intended solely for the personal use of the individual user and is not to be disseminated broadly.

span. As Well (1983) argued, because the estimate of the perceptual span in the moving window paradigm is taken to be the smallest window size that does not disrupt average reading performance, if on some trials the perceptual span is smaller than this window size, the perceptual span size on those trials will not be detected.

There is some evidence that the perceptual span may also vary in picture viewing, another task in addition to reading that requires eye movements. Henderson, Pollatsek, and Rayner (1987, Experiment 1) presented subjects with a display containing two line drawings of objects, one at the fovea and one extrafoveally. The subjects's task was to execute an eye movement to the extrafoveal object and to name it as quickly as possible. Prior to the eye movement, the stimulus at the fovea could be either an object or a meaningless pattern, and the stimulus at the extrafoveal location (the preview) could be either the object to be named (the target) or a no-preview control (an empty box). During the eye movement to the extrafoveal stimulus, the preview was replaced with the target object. The result of interest to us here was that when the meaningless pattern was presented foveally, fixation time on the foveal stimulus prior to the eye movement was significantly shorter than when a meaningful object was presented foveally (247 vs. 252 ms), but extrafoveal preview benefit for the extrafoveal object was significantly greater (86 vs. 70 ms). The results of that experiment are consistent with the results of the present study in that they suggest that the amount of information acquired from an extrafoveal object during picture viewing is affected by the amount of attention devoted to a foveal stimulus.

A second implication of our results concerns so-called "spillover" effects observed in prior studies that have used eye movements as a reflection of cognitive and linguistic processing (e.g., Balota et al., 1985; Ehrlich & Rayner, 1983; Rayner & Duffy, 1986). Spillover effects can be defined as those effects that are expected on word *n* but that are observed on word *n+1* (usually in addition to word *n*). For example, it is sometimes found that if word *n* is difficult, elevated fixation durations are observed on both word *n* and word *n+1*. This finding seems to violate the *immediacy assumption* explicated by Just and Carpenter (1980), which states that fixation time on a word reflects processing for that word but not processing for previous words (i.e., the eyes do not leave a word until all processing of that word is complete). The results of the present study suggest that spillover effects do not necessarily violate the immediacy assumption, because a spillover effect may be due to less availability of parafoveal word information rather than to continued processing at a higher level. In other words, fixation durations on word *n+1* may be elevated when word *n* is difficult because word *n+1* is in fact more difficult to identify.

This explanation of the spillover effects observed in our study does not seem to be totally satisfactory. Fixation times on the parafoveal targets were elevated in Experiment 2 compared with Experiment 1 by an average of 75 ms in the first fixation duration measure (230 vs. 305 ms) and 91 ms in the gaze duration measure (347 vs. 246 ms). Therefore, the difficulty produced by the resolution of the garden path on the foveal word in Experiment 2 continued to influence fixation durations on the subsequent word to a greater extent than would be expected on the basis of the loss of parafoveal preview information alone. We cannot tell whether this additional elevation in reading times was due to higher level (e.g., syntactic) spillover effects from the disambiguating word or to processing difficulty attributable to the target word itself. We conclude that although spillover effects may partially be due to continued processing of the prior word at higher levels, our data suggest that they may also be attributed in part to the loss of parafoveal preview information.

Finally, our results have implications for models of eye movement control in reading. In order to explore these implications, we will first present the Morrison (1984) model of eye movement control and then offer a modification to the model that will account for the present results.

Implications for Eye Movement Control in Reading

Several theorists have proposed that the selective acquisition of information prior to an eye movement from the location about to be fixated is due to the orienting of visual–spatial attention to that location (Henderson et al., 1989; Klein, 1980; McConkie, 1979; Morrison, 1984; Shepherd et al., 1986). In the most completely explicated model, Morrison (1984) proposed that at the beginning of an eye fixation, attention is focused on word *n*, the word centered on the retina. When a preset criterion level of processing for word *n* is reached, attention shifts to the next word, word *n+1*. The shift of attention automatically initiates eye movement programming, and the spatial target of the eye movement is taken to be the new attended location, word *n+1*. This model provides an elegant account of many aspects of eye movement behavior in reading (see Morrison, 1984; Rayner & Pollatsek, 1989). An important point for our purposes is that the model can account for the asymmetry of the perceptual span. Specifically, because the model assumes that visual–spatial attention shifts to the location that will be fixated next prior to a saccadic eye movement, it predicts that information acquisition should be enhanced from the location about to be fixated (Henderson et al., 1989).

Because a good deal of time (estimates range from about 150 ms to over 200 ms) is required to complete and execute the eye movement program (Arnold & Tinker, 1939; Rayner, Slowiaczek, Clifton, & Bertera, 1983; Salthouse & Ellis, 1980), Morrison (1984) proposed that attention may sometimes shift again, to word *n+2*, prior to the movement of the eyes. In these cases, Morrison proposed that *parallel programming* can occur (Becker & Jurgens, 1979) in such a way that computations will begin on a second program prior to execution of the first program. Parallel programming can lead to a state in which the system has aspects of two programs simultaneously active. When computations begin on a second eye movement program before execution of the first, several eye movement behaviors can occur. If the computations begin on the second program before the first program is sufficiently advanced, the first program may simply be cancelled. In this case, the position that would have been the target of the first program (word *n+1*) will be skipped. This aspect of the model can account for the finding that words are sometimes skipped

This document is copyrighted by the American Psychological Association or one of its allied publishers.
This article is intended solely for the personal use of the individual user and is not to be disseminated broadly.

during reading (Just & Carpenter, 1980; Rayner, 1978). Further, because attention remains focused on a word only until processing is completed to the criterion level, the easier word *n+1* is to process, the more likely it is to reach the criterion early and the more likely attention is to shift to word *n+2* early. This aspect thus accounts for the finding that easier words (such as those that are more predictable, have a higher frequency, or are shorter) are more likely to be skipped (see Rayner & Pollatsek, 1987).

If computations begin on the second eye movement program only after computations on the first program are fairly advanced, then the programs may interfere with each other. In this case, an eye fixation on a position between the two targets may occur (Becker & Jurgens, 1979). Readers prefer to place their fixations near or slightly to the left of the center of a word (Dunn-Rankin, 1978; Hyona, Niemi, & Underwood, 1989; McConkie, Kerr, Reddix, & Zola, 1988; Rayner, 1979; O'Regan, 1981). However, fixations in other less advantageous locations, such as between words, are also observed in eye movement data (e.g., McConkie et al., 1988). These fixations can be explained at least in part by interference between simultaneous programs (Morrison, 1984). Finally, if computations begin on the second eye movement program only after computations on the first program are near completion or are completed (but prior to execution of the first program), then the second program may be completed soon after execution of the first. In these cases, the eyes will land on word *n+1* due to execution of the first program. However, because the second program is ready to be executed, fixation time on word *n+1* will be brief, and the eyes will move on to word *n+2* (Becker & Jurgens, 1979). This type of parallel programming can explain the occurrence of fixation durations that are too brief to allow a new program to be readied (Rayner & Pollatsek, 1989).

So far, the Morrison (1984) model uses relatively few processing assumptions to account for a substantial proportion of the eye movement behavior observed in reading. However, the model makes a prediction that was not supported by the results of the experiments reported in this article. According to the Morrison model, extrafoveal word processing does not begin until visual attention shifts from word *n* at the fovea to word *n+1* in the parafovea. Because the shift of attention automatically initiates saccadic programming and because saccadic programming time is assumed to be constant, the eyes will follow the shift of attention by a constant time lag. Extrafoveal word processing can be considered a function of the duration of this time lag. Because extrafoveal processing does not begin until attention shifts away from the fovea, the amount of time that attention remains at the fovea will not affect extrafoveal processing. The Morrison model thus predicts that foveal processing difficulty should not affect the amount of information acquired extrafoveally. Contrary to this prediction, we demonstrated in Experiments 1 and 2 that foveal processing difficulty did affect parafoveal information acquisition.

Our results appear to be very damaging to the Morrison model. However, given the model's simplicity and prior success, it seems that abandonment might be premature. We will next outline a modification to the Morrison model that preserves much of its simplicity while allowing it to account for the new results (Henderson, 1988). This modification is offered as a hypothesis in need of further empirical validation.

Following Morrison (1984), we assume that attention shifts from word *n* to word *n+1* once a criterion level of processing has been completed on word *n*.[4] An eye movement subsequently follows the attentional movement after a lag corresponding to the eye movement programming time. This leads to parafoveal processing of word *n+1* for a duration equal to the eye movement programming time. To the basic model we add the assumption that there is an upper limit on the duration of a fixation, so that an eye fixation will be held only for a limited amount of time. In order for the eye movement system to meet this fixation duration cutoff, we propose that an *eye movement programming deadline* exists equal to the fixation cutoff minus average programming time (see Figure 1). Under normal circumstances, the shift of attention will occur soon enough so that the attentional processing time on word *n* will be less than the programming deadline. In these cases, Morrison's assumptions hold, and parafoveal processing of word *n+1* will last for the entire eye movement programming duration. However, when foveal processing is difficult, attention may remain focused on word *n* for a relatively long period of time. In these cases, attention may not shift prior to the programming deadline. Eye movement programming will therefore begin before attention shifts to word *n+1*. If attention subsequently shifts to word *n+1*, parafoveal processing time on word *n+1* will be reduced by the difference in time between when the deadline was reached and when attention shifted; this would account for the reduced preview benefit observed with foveal processing difficulty observed in Experiments 1 and 2.

Retaining the parallel programming assumption and the assumption that the locus of attention is the location to which the eyes are programmed to move (Morrison, 1984), several additional eye movement behaviors can be accounted for by the programming deadline assumption. First, consider the case where attention remains focused on word *n* well past the programming deadline. In this case, the deadline is reached, programming begins, and the location parameter is taken to be word *n* (because it is the current focus of attention). If attention does not subsequently shift prior to a "point of no return" beyond which the program can no longer be modified, then the word that is currently being fixated will be the target of the next eye movement program. This straightforwardly predicts that when word *n* is difficult enough, it will receive consecutive fixations, a ubiquitous finding in the eye movement literature (see Just & Carpenter, 1987; Rayner & Pollatsek, 1989). Interestingly, one of the areas of difficulty for the Morrison model was its inability to account for consecutive fixations within a word (Rayner & Pollatsek, 1989). The

---

[4] Although we will follow other theorists and use the term *shift* to describe the spatial change in attentional focus, we wish to remain neutral on the question of whether the change is due to an actual movement of an attentional spotlight (e.g., Posner, 1980; Tsal, 1983) or a change in the location of a peak in an attentional gradient (e.g., LaBerge & Brown, 1989; Shulman, Wilson, & Sheehy, 1985).

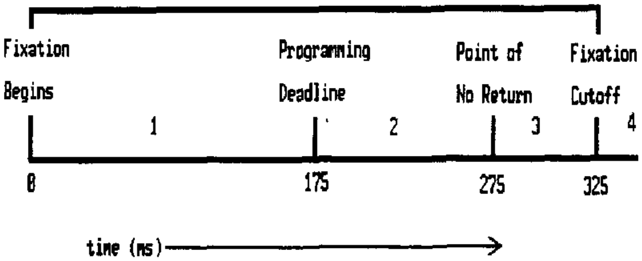

Figure 1. An illustration of four possible preview cases according to the programming deadline hypothesis. ([1] When attention shifts to word *n+1* prior to the programming deadline, preview benefit for word *n+1* is maximal. [2] When attention shifts to word *n+1* following the programming deadline but prior to the point of no return, preview benefit for word *n+1* is reduced. [3] When attention shifts to word *n+1* following the point of no return, word *n* will briefly be fixated again and preview benefit for word *n+1* is reduced. [4] When attention does not shift to word *n+1* prior to the fixation cutoff, word *n* is fixated again. Note: The times used for the programming deadline, point of no return, and fixation cutoff were arbitrarily chosen for purposes of the example.)

finding that consecutive fixations within a word are often located at different letter positions may be accounted for by a combination of several factors, including noise in the eye movement programming system and small changes in the center of focus of attention within the word.

The second case consists of those fixations when attention remains focused on word *n* past the programming deadline but then shifts to word *n+1* soon after the deadline is reached. When the deadline is reached, an eye movement will be programmed, taking word *n* as the target. However, when attention shifts to word *n+1*, the program to move to word *n* will be cancelled, and the eyes will be sent to word *n+1*. In this case, attention will precede the eyes to word *n+1* by less than the usual full eye movement programming duration, and the amount of information acquired from word *n+1* will be reduced. This case, then, can account for the reduced preview benefit found when word *n* is difficult.

A final interesting case occurs when the shift of attention occurs too late after the deadline to completely cancel the program to fixate on word *n* again but soon enough to reorganize the command (i.e., prior to the point of no return). Here, the two programs will temporally overlap, and the eyes will refixate word *n* for a brief amount of time and then move on to word *n+1*. Again, this type of eye movement behavior can be observed in typical reading, and it can not easily be accounted for by Morrison (1984). In this case, because attention moves following the programming deadline, the amount of preview benefit derived from word *n+1* will be reduced even though the gaze duration on word *n* will be increased, a result observed in our experiments.

Adding the programming deadline assumption to the original Morrison model greatly increases its ability to account for the types of eye movement behaviors observed during reading. Is there any independent evidence for such a fixation cutoff? Two studies that directly manipulated the point in time during a fixation when foveal information became available provide such evidence (Morrison, 1984; Rayner & Pollatsek, 1981). In these studies, the foveal text could appear either coincidently with the beginning of the fixation or after some delay (in the delay conditions, a spatial mask occupied the foveal position for the duration of the delay). In both studies, readers sometimes moved their eyes to the next word prior to the end of the delay, so that the foveal text was never seen. These "anticipatory" eye movements were far more likely as the mask delay increased (Morrison, 1984; Rayner & Pollatsek, 1981). For example, when the mask was five characters in size, a delay of 0 ms caused few anticipatory saccades, a delay of 200 ms caused anticipations on about 25% of the trials, and a delay of 350 ms caused anticipations on about 70% of the trials (Morrison, 1984). These data are consistent with the hypothesis that there is a tendency in the eye movement system to keep the eyes moving, as we propose in the programming deadline hypothesis. The increased probability of moving as the mask delay increases can be accounted for by assuming that the exact point in time of the programming deadline is subject to noise, so that there is a distribution of deadline times around the actual deadline from trial to trial. Interestingly, anticipatory saccades were found to be equally likely whether the duration of the delay was random or constant across a block of trials. Presumably, the best strategy for the reader in the blocked condition would have been to wait for the delay to end so that the word could be read. Instead, there was an overwhelming tendency for the eyes to move away from the position before the delay was over if the delay was 350 ms. Again, these data are consistent with the programming deadline hypothesis. Finally, Morrison (1984) and Rayner and Pollatsek (1981) found that when anticipatory saccades were removed from the data, a given delay led to an equal lengthening of fixation duration. This result can be interpreted to suggest that the duration of a fixation is under direct control of the attentional system except when the deadline is reached (see Rayner & Pollatsek, 1981).[5]

Finally, as mentioned in the introduction, several studies have shown that even under tachistoscopic viewing conditions increased foveal load leads to decreased extrafoveal information acquisition. This effect has sometimes been called the *tunnel vision* effect (Mackworth, 1965) because it has been found that the distance from which information can be ac-

---

[5] The programming deadline hypothesis makes another clear prediction: Fixation times on a word should be bimodally distributed, with one peak in the distribution corresponding to the fixations that leave the word prior to the deadline and the other peak corresponding to fixations terminated by the deadline. In Morrison's (1984) data, there was a strong tendency for bimodality to appear as the duration of the foveal stimulus onset delay increased. In the present experiments, this bimodality would be expected to be more obvious when the foveal word was more difficult, because in those conditions the mode due to the deadline should be more pronounced. Although a post hoc analysis of the first fixation duration distributions offered a hint of bimodality, because there were at most 40 data points per subject in the difficult foveal word condition in either experiment, it was difficult to discern whether the bimodality was real or was simply due to a less pronounced single mode in the difficult foveal word conditions. We are currently planning a study in which we intend to directly test the bimodality prediction.

This document is copyrighted by the American Psychological Association or one of its allied publishers.
This article is intended solely for the personal use of the individual user and is not to be disseminated broadly.

This document is copyrighted by the American Psychological Association or one of its allied publishers.
This article is intended solely for the personal use of the individual user and is not to be disseminated broadly.

quired becomes smaller when foveal processing is more difficult (i.e., foveal load and retinal eccentricity interact; Ikeda & Takeuchi, 1975; Williams, 1982, 1985; but see Holmes et al., 1977). The usual interpretation of this effect has been that attention is shared between foveal and extrafoveal stimuli. Our analysis of eye movement control suggests an alternative account. It could be that even in tachistoscopic viewing conditions, subjects sequentially attend first to the foveal stimulus and then to the extrafoveal stimulus (Holmes et al., 1977, proposed a view similar to this). On this hypothesis, the reason that less information is acquired from extrafoveal stimuli when foveal processing is more difficult is that attention is more likely to remain on the foveal stimulus until after the display has been terminated. The interaction with eccentricity that is sometimes found need not be attributed to a "shrinking" perceptual span. Instead, it could be due to attention taking longer to reach a more eccentric stimulus, perhaps because the visual system has relatively greater difficulty locating a more peripheral stimulus in order to direct attention to it. We believe that this issue is worthy of further investigation.

Conclusion

In this article we explored the hypothesis that the perceptual span during reading changes as a function of foveal processing difficulty. By independently manipulating the difficulty of the word under fixation and the type of information available in the next (parafoveal) word, we were able to show that less information is acquired parafoveally when foveal processing is difficult. This result was found regardless of whether the difficulty of the foveal word was manipulated lexically or syntactically. Thus, the results confirm the hypothesis that the perceptual span varies with foveal processing difficulty. This conclusion contrasts with a view of the perceptual span in which the size of the perceptual span is determined by perceptual factors such as acuity or lateral masking. Instead, it could be argued that the perceptual span may better be though of as the *attentional span.*

Finally, we should note that we have operationalized the perceptual span in the present study as the amount of information acquired from the parafoveal word that is immediately to the right of the word under fixation. However, it is important to note that the perceptual span is probably not unitary, but instead consists of a number of "subspans," each dependent on the type of information acquired (Rayner & Pollatsek, 1987). For example, while the perceptual span for information used in computing future fixation positions (i.e., the spaces between words; Morris, Pollatsek, & Rayner, in press; Pollatsek & Rayner, 1982) extends to 15 characters to the right of the fixation point, the perceptual span for letter identification is smaller, extending from the currently fixated word to the first few letters of the next word (Lima, 1987; Lima & Inhoff, 1985; Pollatsek, Rayner, & Balota, 1986; Rayner et al., 1982). Clearly, in the present study we were testing something more like the letter span than the total perceptual span. On one view, while the attentional spotlight may be required for acquiring letter identity information, acquiring space information may be preattentive and therefore immune to the effects of foveal processing difficulty. In a sense, we have been assuming that word location is acquired preattentively; otherwise, it is not clear how attention could be directed to the appropriate parafoveal location prior to the eye movement. However, it is at this point an open empirical question whether foveal difficulty would affect the acquisition of other types of information used during reading such as the letter spaces between words.

References

Arnold, D. C., & Tinker, M. A. (1939). The fixational pause of the eyes. *Journal of Experimental Psychology, 25,* 271–280.

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

Balota, D. A., & Rayner, K. (1983). Parafoveal visual information and semantic contextual constraints. *Journal of Experimental Psychology: Human Perception and Performance, 9,* 726–738.

Becker, C. A., & Killion, T. H. (1977). Interaction of visual and cognitive effects in word recognition. *Journal of Experimental Psychology: Human Perception and Performance, 3,* 389–401.

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

Bryden, M. P. (1961). The role of post-exposural eye movements in tachistoscopic perception. *Canadian Journal of Psychology, 15,* 220–225.

Crovitz, H. F., & Daves, W. (1962). Tendencies to eye movement and perceptual accuracy. *Journal of Experimental Psychology, 63,* 495–498.

DenBuurman, R., Boersema, T., & Gerrisen, J. F. (1981). Eye movements and the perceptual span in reading. *Reading Research Quarterly, 16,* 227–235.

Dunn-Rankin, P. (1978). The visual characteristics of words. *Scientific American, 238,* 122–130.

Ehrlich, K., & Rayner, K. (1983). Pronoun assignment and semantic integration during reading: Eye movements and immediacy of processing. *Journal of Verbal Learning and Verbal Behavior, 20,* 641–655.

Ferreira, F., & Clifton, C. (1986). The independence of syntactic processing. *Journal of Memory and Language, 25,* 75–87.

Ferreira, F., & Henderson, J. M. (in press). The use of verb information in syntactic parsing: Evidence from eye movements and word-by-word self-paced reading. *Journal of Experimental Psychology: Learning, Memory, and Cognition.*

Frazier, L., & Rayner, K. (1982). Making and correcting errors during sentence comprehension: Eye movements in the analysis of structurally ambiguous sentences. *Cognitive Psychology, 14,* 178–210.

Henderson, J. M. (1988). *Visual attention and the acquisition of extrafoveal information during eye fixations.* Unpublished doctoral dissertation, University of Massachusetts, Amherst, MA.

Henderson, J. M., Pollatsek, A., & Rayner, K. (1987). Effects of foveal priming and extrafoveal preview on object identification. *Journal of Experimental Psychology: Human Perception and Performance, 13,* 449–463.

Henderson, J. M., Pollatsek, A., & Rayner, K. (1989). Covert visual attention and extrafoveal information use during object identification. *Perception & Psychophysics, 45,* 196–208.

Holmes, D. L., Cohen, K. M., Haith, M. M., & Morrison, F. J. (1977). Peripheral visual processing. *Perception & Psychophysics, 22,* 571–577.

Hyona, J., Niemi, P., & Underwood, G. (1989). Reading long words embedded in sentences: Informativeness of word halves affects eye movements. *Journal of Experimental Psychology: Human Percep-*

This document is copyrighted by the American Psychological Association or one of its allied publishers.
This article is intended solely for the personal use of the individual user and is not to be disseminated broadly.

tion and Performance, 15, 142–152.

Ikeda, M., & Takeuchi, T. (1975). Influence of foveal load on the functional visual field. *Perception & Psychophysics, 18,* 255–260.

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

Inhoff, A. W. (1987). Lexical access during eye fixations in sentence reading: Effects of word structure. In M. Coltheart (Ed.), *Attention and performance XII* (pp. 403–420). London: Erlbaum.

Inhoff, A. W., Pollatsek, A., Posner, M. I., & Rayner K. (1989). Covert attention and eye movements in reading. *Quarterly Journal of Experimental Psychology, 41A,* 63–89.

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

Just, M. A., & Carpenter, P. A. (1980). A theory of reading: From eye fixations to comprehension. *Psychological Review, 87,* 329–354.

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

Klein, R. (1980). Does oculomotor readiness mediate cognitive control of attention? In R. S. Nickerson (Ed.), *Attention and performance VIII* (pp. 259–276). Hillsdale, NJ: Erlbaum.

Kučera, H., & Francis, W. N. (1967). *Computational analysis of present-day American English.* Providence, RI: Brown University Press.

LaBerge, D., & Brown, V. (1989). Theory of attentional operations in shape identification. *Psychological Review, 96,* 101–124.

Lima, S. D. (1987). Morphological analysis in sentence reading. *Journal of Memory and Language, 26,* 84–99.

Lima, S. D., & Inhoff, A. W. (1985). Lexical access during eye fixations in reading: Effects of word-initial letter sequence. *Journal of Experimental Psychology: Human Perception and Performance, 11,* 272–285.

Mackworth, N. H. (1965). Visual noise causes tunnel vision. *Psychonomic Science, 3,* 67–68.

McClelland, J. L., & O'Regan, J. K. (1981). Expectations increase the benefit derived from parafoveal visual information in reading words aloud. *Journal of Experimental Psychology: Human Perception and Performance, 7,* 634–644.

McConkie, G. W. (1979). On the role and control of eye movements in reading. In P. A. Kolers, M. E. Wrolstad, & H. Bouma (Eds.), *Processing of visible language* (Vol. 1, pp. 37–48). New York: Plenum Press.

McConkie, G. W., Kerr, P., 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.

McConkie, G. W., & Rayner, K. (1975). The span of the effective stimulus during a fixation in reading. *Perception & Psychophysics, 17,* 578–586.

McConkie, G. W., & Rayner, K. (1976). Asymmetry of the perceptual span in reading. *Bulletin of the Psychonomic Society, 8,* 365–368.

Morris, R. K., Pollatsek, A., & Rayner, K. (in press). Eye movement guidance in reading: The role of parafoveal letter and space information. *Journal of Experimental Psychology: Human Perception and Performance.*

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

Morton, J. (1969). Interaction of information in word recognition. *Psychological Review, 76,* 165–178.

O'Regan, J. K. (1981). The convenient viewing location hypothesis. In D. F. Fisher, R. A. Monty, & J. W. Senders (Eds.), *Eye movements: Cognition and visual perception.* Hillsdale, NJ: Erlbaum.

Pollatsek, A., Bolozky, S., Well, A. D., & Rayner, K. (1981). Asymmetries in the perceptual span for Israeli readers. *Brain and Language, 14,* 174–180.

Pollatsek, A., & Rayner, K. (1982). Eye movement control in reading: The role of word boundaries. *Journal of Experimental Psychology: Human Perception and Performance, 8,* 817–833.

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

Posner, M. I. (1980). Orienting of attention. *Quarterly Journal of Experimental Psychology, 32,* 3–25.

Rayner, K. (1975). The perceptual span and peripheral cues in reading. *Cognitive Psychology, 7,* 65–81.

Rayner, K. (1978). Eye movements in reading and information processing. *Psychological Bulletin, 85,* 618–660.

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

Rayner, K. (1986). Eye movements and the perceptual span in beginning and skilled readers. *Journal of Experimental Child Psychology, 41,* 211–236.

Rayner, K., & Bertera, J. H. (1979). Reading without a fovea. *Science, 206,* 468–469.

Rayner, K., Carlson, M., & Frazier, L. (1983). The interaction of syntax and semantics during sentence processing: Eye movements in the analysis of semantically biased sentences. *Journal of Verbal Learning and Verbal Behavior, 22,* 358–374.

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., & Frazier, L. (1987). Parsing temporarily ambiguous complements. *Quarterly Journal of Experimental Psychology, 39A,* 657–673.

Rayner, K., Inhoff, A. W., Morrison, R. E., Slowiaczek, M. L., & Bertera, J. H. (1981). Masking of foveal and parafoveal vision during eye fixations in reading. *Journal of Experimental Psychology: Human Perception and Performance, 7,* 167–179.

Rayner, K., McConkie, G. W., & Ehrlich, S. F. (1978). Eye movements and intergrating information across fixations. *Journal of Experimental Psychology: Human Perception and Performance, 4,* 529–544.

Rayner, K., McConkie, G. W., & Zola, D. (1980). Integrating information across eye movements. *Cognitive Psychology, 12,* 206–226.

Rayner, K., Murphy, L. A., Henderson, J. M., & Pollatsek, A. (1989). Selective attentional dyslexia. *Cognitive Neuropsychology, 6,* 357–378.

Rayner, K., & Pollatsek, A. (1981). Eye movement control during reading: Evidence for direct control. *Quarterly Journal of Experimental Psychology, 33A,* 351–373.

Rayner, K., & Pollatsek, A. (1987). Eye movements in reading: A tutorial review. In M. Coltheart (Ed.), *Attention and performance XII* (pp. 327–362). London: Erlbaum.

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

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

Rayner, K., Well, A. D., & Pollatsek, A. (1980). Asymmetry of the effective visual field in reading. *Perception & Psychophysics, 27,* 537–544.

Rayner, K., Well, A. D., Pollatsek, A., & Bertera, J. H. (1982). The availability of useful information to the right of fixation in reading. *Perception & Psychophysics, 31,* 537–550.

Remington, R. W. (1980). Attention and saccadic eye movements. *Journal of Experimental Psychology: Human Perception and Performance, 6,* 726–744.

Salthouse, T. A., & Ellis, C. L. (1980). Determinants of eye fixation duration. *American Journal of Psychology, 93,* 207–234.

Shepherd, M., Findlay, J. M., & Hockey, R. J. (1986). The relationship between eye movements and spatial attention. *Quarterly Journal of Experimental Psychology, 38A,* 475–491.

Shulman, G. L., Wilson, J., & Sheehy, J. B. (1985). Spatial determinants of the distribution of attention. *Perception & Psychophysics, 37,* 59–65.

Tsal, Y. (1983). Movements of attention across the visual field. *Journal of Experimental Psychology: Human Perception and Performance, 9,* 523–530.

Underwood, N. R., & McConkie, G. W. (1985). Perceptual span for letter distinctions during reading. *Reading Research Quarterly, 20,* 153–162.

Well, A. D. (1983). Perceptual factors in reading. In K. Rayner (Ed.), *Eye movements in reading: Perceptual and language processes* (pp. 141–150). New York: Academic Press.

Williams, L. J. (1982). Cognitive load and the functional field of view. *Human Factors, 24,* 683–692.

Williams, L. J. (1985). Tunnel vision induced by a foveal load manipulation. *Human Factors, 27,* 221–227.

Appendix

High- and Low-Frequency Foveal Words Used in Experiment 1

High	Low	High	Low
1. chest	trunk	19. older	elder
2. winter	autumn	20. travel	wander
3. window	portal	21. practice	skirmish
4. plant	hedge	22. happy	merry
5. battle	combat	23. weather	climate
6. speak	orate	24. weapon	pistol
7. swing	swipe	25. hotel	lodge
8. command	mandate	26. flower	orchid
9. simple	stupid	27. market	bazaar
10. bother	pester	28. person	orphan
11. danger	hazard	29. minister	cardinal
12. describe	portray	30. spring	geyser
13. servant	butler	31. problem	dilemma
14. guide	escort	32. avoid	elude
15. house	hovel	33. plastic	plaster
16. picture	etching	34. oppose	hinder
17. approve	endorse	35. report	convey
18. disease	illness	36. money	dowry

Received July 6, 1989
Revision received September 14, 1989
Accepted September 18, 1989 ■

This document is copyrighted by the American Psychological Association or one of its allied publishers.
This article is intended solely for the personal use of the individual user and is not to be disseminated broadly.