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# Time course of visual information utilization during fixations in reading



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# Center for the Study of Reading

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Abstract

College students read short texts from a CRT as their eye movements were being monitored. During selected fixations, the text was briefly masked and reappeared with one word changed. Subjects often were unaware that the word had changed. Sometimes they reported seeing the first presented word, sometimes the second presented word, and sometimes both. When only one word was reported, two factors were found to determine which one it was: the length of time a word was present during the fixation and the predictability of a word in its context. The results suggested that visual information is utilized for reading at a crucial period during the fixation, and that this crucial period can occur at different times on different fixations, which is referred to as the Variable Utilization Time Principle. The pattern of responses also indicated that the first letter of a word is not utilized before other letters and that letters are not scanned from left to right during a fixation.



# The Time Course of Visual Information Utilization During Fixations in Reading

It is well established that the perception of letters and words during reading takes place entirely during fixations (Wolverton, 1979). The question this study deals with is when during a fixation is visual information put to use in furthering the reading process. First, it is necessary to distinguish between the registration of the visual pattern coming from the retina on a given fixation and the utilization of the information provided by that pattern (McConkie, 1983). A light pattern on the retina automatically induces a pattern of neural activity in the visual cortex. This will be called the registration of the stimulus. Sometime later, the registered pattern has an effect on the ongoing reading comprehension process. This will be called the utilization of information. The question of interest, then, is when this utilization of text information occurs. This question can be separated into two different issues. First, does the utilization of visual information take place for the entire time the eye is in fixation, or is there a certain crucial period within the fixation during which this utilization occurs? This will be called the period of utilization question. Second, is utilization of all the information during a fixation accomplished at the same time? That is, is different information utilized at different times during the fixation? This is essentially a question of serial versus parallel processing. It will be referred to as the manner of utilization question.

One answer to the period of utilization question will be referred to as the crucial period hypothesis. According to this hypothesis, there is a

certain interval, or crucial period, within the time period of the fixation during which the available information makes its impact on the reading process. The remainder of the processing then occurs without reference to the visually provided information. If there is a crucial period, it may consistently occupy a certain part of the fixation or it may vary from fixation to fixation. Gough's (1972) model of reading, for instance, posits a fixed crucial period. The visual pattern is registered in the form of an icon, formed at the very beginning of a fixation, and the information is then utilized through a read-out of letters from the icon, which occurs for the remainder of the fixation. Rayner, Inhoff, Morrison, Slowiaczek, and Bertera (1981) have also argued for a fixed crucial period by showing that people can read if visual information is available for only the first 50 msec of each fixation. They masked the text with foveal or full-line masks at different times following the beginning of each fixation, ranging from 0-150 msec, and found that the detrimental effects of masking on reading reached asymptote by 50 msec. Rayner et al.'s results indicate that it is possible to acquire all the new visual information necessary to continue reading within the first 50 msec of each fixation, but this does not necessarily indicate that visual information is utilized only during the first 50 msec when readers are not forced to do so.

The other logical possibility, not proposed in the literature, is that there may be a variable crucial period. That is, the crucial period during which utilization occurs may vary from fixation to fixation. There may be an interval during which visual information is utilized, but it may occur at different times in different fixations. This would occur, for instance, if



readers use visual information only when they are ready to identify the next word, regardless of whether this is at the beginning of a fixation or later in it.

The alternative to the crucial period hypothesis is that all visual information influences the reading process throughout the entire fixation, from beginning to end. Data relevant to this position comes from a series of experiments conducted by Wolverton (Wolverton, 1979, Wolverton & Zola, 1983). While subjects read connected text, the lines of text were replaced for a 30 msec period with either a blank line, a mask of X's, a line of dissimilar text, or a line with visually similar letters. When the replacement occurred during fixations, at 0, 30, 100, or 200 msec after the fixation began, a significant increase in fixation duration occurred. This indicates that the visual system is sensitive to the stimulus pattern throughout the fixation. It does not, however, indicate when this information is obtained and used in reading.

The conclusion from the Rayner et al. (1981) and Wolverton (1979, Wolverton & Zola, 1983) studies seems to be that sufficient visual information to maintain reading can be registered within the first 50 msec of a fixation, but the reader is capable of noticing information at any point during the fixation. The present study attempted to determine the period during which information is typically put to use during fixations as people read, without using a technique which forces this use to occur at a particular time.

With regard to the manner of utilization several hypotheses have been advanced in the literature. A variety of theorists have proposed that letters

are acquired sequentially, from left-to-right, in sensory input (Geyer, 1970) or from a fading postexposural trace (Anderson & Crosland, 1933; Harcum, 1967; Heron, 1957) or icon (Estes & Taylor, 1964; Gough, 1972; Mewhort, Merikle, & Bryden, 1969; Neisser, 1967; Sperling, 1963, 1967). Recent evidence (Mewhort, 1974; Mewhort & Beal, 1977) has lead some current theorists to propose that this scanning mechanism deals with syllables rather than letters (Adams, 1981; Mewhort & Campbell 1981). McConkie (1979) suggests that the region from which information is acquired shifts from left to right within a fixation in reading. Another hypothesis has been that initial letters of words are processed before other letters. For example, Brown (1970) suggested that there is a "noticing order" for different aspects of the stimulus within a fixation, beginning with word lengths and initial and final letters. Finally, several investigators have claimed that all information is acquired simultaneously (Estes, 1972; Johnson, 1975; Sperling, 1970).

The current study is an initial attempt to answer the period of utilization and manner of utilization questions. The basic experimental manipulation was to change the information present in the text at different times during a fixation, in a way that preserves the continuity of the text, and then observe what subjects report having read. To do this, pairs of five letter words were identified which differed in only a single letter, e.g. tombs and bombs. Texts were written into which either one of these words would fit appropriately, e.g. The underground caverns were meant to house hidden (tombs,bombs), but then the construction was stopped because of lack of funds. The result is actually two texts which differ by a single letter. Subjects read these texts from a cathode ray tube (CRT) while their eye



movements were being monitored. As they read, the single letter was switched to its alternative partway during certain fixations, e.g. the letter t in tombs was changed to a b, making the word bombs. Changing this single letter consequently changes the word and the meaning of the text. As the subjects read, one version of the text was present on the CRT during the early part of each fixation, and the other version during the latter part of each fixation. If subjects in this situation always see both words, this would indicate that utilization of visual information occurs continuously throughout the fixation, not just during a crucial period. If subjects frequently see only one of the words, this would suggest the presence of a crucial period. In this latter case, subjects may show consistency in reporting the first or second word presented during the fixation, or may show variability in which word they report. Consistent reporting would serve as evidence for a fixed crucial period, while variability in which word is seen would suggest a variable crucial period.

Pilot studies indicated that subjects typically saw the letter change while they were reading. However, this does not necessarily mean that information is normally acquired and used for reading during the entire fixation. Since the change occurred during a fixation, when the visual system is very sensitive to detecting movement, it is likely that the apparent movement occurring as the letters changed was catching the subject's attention. To help eliminate the attention catching effects of this apparent movement, a general disruption of the line of text was produced by briefly replacing it with a mask of capital X's while the letters were switched. The mask caused apparent movement at all letter positions in the line of text, so

that attention could not be attracted to a single letter position, i.e. the position at which the change was made. It was assumed that under these conditions, the changing letter would not be detected on the basis of localized movement. Rather, such detection would indicate either sensing of a difference in the stimulus pattern present early versus later in the fixation, or sensing the change in the word or its meaning. In either case, this would suggest the use of the visual information both before and following the mask. Since the mask should have effects in addition to the effects of the switching letter manipulation, two control conditions were used: one with masking and no letter change and one with no display changes at all. Pilot studies indicated that the shortest mask duration which would be effective was 30 msec.

In regards to the period of utilization, the prediction of the crucial period hypothesis is clear: if information is only utilized during a fixed interval, then subjects should consistently report seeing the first or the second word which was presented during a fixation, depending on whether the crucial period occurs early or late in the fixation. If there is a variable crucial period, then subjects should sometimes report seeing the first and sometimes the second word which was presented.

To investigate the manner of utilization question two other manipulations were added. First, the time of the display change was varied by using three mask onset time conditions. The onset of the mask could occur 50, 80, or 120 msec after the onset of fixation, making the onset of the alternative text 80, 110, or 150 msec after fixation onset. Second, the letter which was switching could occur in the first letter position of the word, e.g. beads versus



heads, or in the fourth letter position, e.g. shaky versus shady. In this situation, the left-to-right serial utilization hypothesis makes two predictions. First, there should be a trend in which word is reported across the three mask onset times. As mask onset time increases, the first word should be reported more often and the second word should be reported less often. That is, the longer the time the first word is present, the more likely it is that the sequential scan would reach the critical letter during that period. Similarly, the longer the time the second word is present, the more likely it is that the scan would reach that letter position during that period. Second, the likelihood of reporting the first or second presented word should be different when the fixation on which the word was identified is to the left of the switching letter as compared to when it is to the right of the switching letter. When the fixation is to the right, the switching letter is on the left side of the visual field, where the scan is believed to begin, so the scan should more often reach the switching letter while the first word is present. Conversely, when the fixation is to the left, the switching letter is to the right, and will be reached later in the fixation, making it more likely that the second word will be reported. In other words, a dynamic trend in reporting the first or second word should appear across the position of the fixation relative to the switching letter.

If the initial letters of words are utilized before other letters, then a different prediction is made. At any mask onset time, the first word should be more likely to be reported if the critical letter is the initial letter of the word than if it is the fourth letter. The initial-letters-first hypothesis also predicts that whether the first or second word is reported

should not be related to the position of the fixation relative to the switching letter. It might be noted that if left-to-right scanning is assumed to take place on word units, then this differential trend between words switching in the first and fourth letters is also expected by this hypothesis.

The simultaneous utilization hypothesis predicts an absence of all of the above trends for single word reporting.

## Methods

### Subjects

Sixteen University of Illinois undergraduates served as subjects. They all had normal, uncorrected vision, were native speakers of English, and were paid for their participation in the experiment. They had been selected so as not to have certain ocular or facial characteristics which make eye movement monitoring difficult. None of the subjects had previously participated in an eye movement experiment.

### Apparatus

The text was displayed one line at a time on a Digital Equipment Corporation Model VT-11 display unit, having a hardware character generator with upper and lower case characters. Display changes are made in about 3 msec without interrupting the refresh cycle. The distance between the subject and the CRT was 48 cm., which made one degree of visual angle equivalent to 4 character positions. The subject was supplied with a button which called up the next line of text onto the CRT. This allowed subjects to read multi-line



passages one line at a time at their own pace, although it was not possible for them to reread a previous line. Eye movements were monitored with a Stanford Research Institute Dual Purkinje Image Eyetracker. Both the CRT and the eyetracker were interfaced with a Digital Equipment Corporation PDP-11/40 computer. The computer was programmed to sample eyeposition every millisecond.

### Materials

Ninety-six pairs of short texts were written which were different in meaning but were physically different in only one letter. These texts were created by first identifying pairs of five letter words which differed in a single letter, half at the first letter position and half at the fourth, and then writing a context of one to three sentences in which either member of a word pair fit and made sense at the same position in the text. As a result, there were two different versions of each text distinguished by a single letter in one word. The letter which distinguishes the two texts will be referred to as the critical letter and the word containing the critical letter will be called the critical word. The critical word always appeared at least sixteen character positions away from the beginning or end of a line.

In order to assess whether any member of a word pair fit into its corresponding text more appropriately or was more predictable than the other alternative, a norming questionnaire was given to 30 subjects, who did not participate in the main study. These subjects were given each passage up to and including the critical word, but with a blank in the position of the critical letter. Their task was to supply the missing letter. The results

were used in later analyses. The texts used in the study along with the responses from the norming questionnaire for each text are given in Blanchard, McConkie, and Zola (1982).

Sixteen additional short texts were used for the no-mask control condition. These were texts originally constructed for another study to contain pairs of five letter words differing in the second or third letter. In the present study, all subjects saw only one of the two alternative versions of each of these texts. Likewise, twelve more of these texts were used as warm-up texts, and nine others as a practice set.

Design

In this study, display changes were made during fixations in reading. During each fixation, the text was replaced with a mask for 30 msec, after which text reappeared for the rest of the fixation. The mask consisted of a solid line of upper case X's the same length as the line it replaced. The manipulation divides the fixation into three periods: a pre-mask, mask, and post-mask period. The duration of the pre-mask period was determined by the onset of the mask, which was delayed either 50, 80, or 120 msec after the beginning of the fixation. The duration of the post-mask period varied depending on the length of time remaining in the fixation. In the experimental condition, when the text reappeared the critical letter had been changed, replacing the first critical word with its alternate. Figure 1 depicts a sequence of displays which appeared during fixations in the experimental condition. At the beginning of the each saccade, the line of text reverted to the original line of text, containing the first alternative



word. Thus, one word was always present during the early part of the fixation and the other word during the latter part. In the no-switch control condition (which will also be referred to as simply the control condition) when the text reappeared after the mask the same critical letter was present. In other words, in the experimental condition, the alternate line was present during the post-mask period, while in the no-switch control condition, the same line was present during the pre- and post-mask periods.

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Insert Figure 1 about here

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The computer was programmed to make the letter change in the experimental condition only when a fixation fell within the immediate region of the critical word. This region was defined by setting three boundaries on each line containing a critical word. The first, the enabling boundary, was always 12 character positions to the right of the beginning of the line. No letter change occurred until the eyes had fixated at least once to the left of this boundary. The second, the initiating boundary, was 11 character positions to the left of the first letter of the critical word. The first letter change occurred during the first fixation to the right of the initiating boundary, provided that the eyes had previously fixated left of the enabling boundary. These changes continued on each fixation until the subject crossed the terminating boundary, which was 11 character positions to the right of the first letter of the critical word. Crossing this boundary terminated the letter changes, and they did not occur again, even if the eyes later returned

to the region of the critical word. On all other fixations the mask occurred at its scheduled time, but the line of text that came on after it was the same as the text present prior to it.

There were two control conditions and one experimental condition in this experiment. The experimental and no-switch control conditions occurred in the main group of ninety-six short texts which subjects read following the warm-ups. Seventy-two of these texts were in the experimental condition and twenty-four were in the no-switch control condition. Which texts served in these conditions was counterbalanced across subjects, as well as which of the two alternative words was present at the beginning of each fixation. Each mask onset time occurred equally often in these two conditions for each subject. After the subjects finished reading the main group of ninety-six texts, they were given sixteen additional texts to read. These texts constituted the no-mask control condition, in which no experimental manipulations occurred: the text was never replaced by the mask and the critical letters were never switched.

Procedure

A bitebar and headrest were used in order to minimize head movements during the reading session. Following the adjustment of the eyetracking equipment, subjects were given the nine practice texts to read, in order to become acquainted with the experimental task. If there were no further problems with eyetracker adjustment at this point, the experiment continued with the reading of the main group of texts. Subjects read these texts in twelve trials of nine texts each, which included a warm-up text placed at the



beginning of each trial. A short rest was taken between trials. After reading the main group of texts, subjects read the sixteen no-mask control texts in two trials.

After reading each text, four test words appeared on the CRT, one at a time. The subjects were instructed to indicate, for each word, whether or not it had appeared in the immediately preceding text. They did this by pressing one of two buttons, one to indicate "no" and the other to indicate "yes." No feedback was given as to the correctness of the responses. Two of the four test words were the two critical words. The other two test words, like the two critical words, differed by only a single letter. However, only one of these two foil words was actually present in the text. Note that in each test set for texts in the experimental condition, three test words had actually been in the text and one had not. In the no-switch and no-mask control conditions only two of the four test words had been present in the text. The order of presentation of the test words was randomized across texts.

Before reading the warm-up texts, the subjects were told about the mask and were given instructions on how to respond to the test words. They were also told that words would occasionally change. It was emphasized that they should respond "yes" to all words they actually saw. After reading the warm-up texts, subjects were asked if they had seen any words change. After they had read the main group of texts in the experimental and no-switch control conditions, the subjects were again asked if they had seen any words change.

## Results

### Responses to the Test Words

The principal data consists of the critical word or words subjects reported seeing. The term "response" will be used to refer to which critical word or words subjects reported seeing on the test presented to them after reading each text. That is, a response may consist of reporting the first presented word, the second presented word, both words, or neither word. Of the responses in the experimental condition, 65% were reports of only one of the critical words: 29% were reports of the first presented word and 36% were reports of the second presented word. All subjects showed this same pattern of sometimes reporting the first word and sometimes reporting the second, with the first word being indicated by different subjects from 11% to 46% of the time and the second word from 19% to 51% of the time. Even though subjects were informed of the display change before the experiment, they frequently were unaware that a change had taken place. Subjects' estimates of how often they saw changes indicate they were aware of them only on a minority of the experimental texts.

That subjects were frequently unaware of a change and that they usually reported seeing only one of the critical words suggests a crucial period hypothesis. Furthermore, the pattern of results also suggests a variable crucial period, since subjects sometimes reported seeing the first word and sometimes the second. In particular, contrary to the findings of Rayner et al. (1981), the crucial period often occurs after the first 50 msec of a fixation. Of the instances where the second word was reported, that word was



never present during the first 50 msec. In fact, in 12% of those cases in which the second word was reported, that word was present only in the last 30 msec or less of the fixation.

The top of Figure 2 shows the frequencies of reporting the first, second, or both words for each mask onset time in the experimental condition. These frequencies are significantly different ($\chi^2(2) = 102.58$, $p \sim 0$) and show a trend, viz. the longer the time the first word was present, the more likely it was to be reported and the less likely the second word was to be reported. This is again consistent with the variable crucial period hypothesis, for the longer the first word was present, the greater the likelihood that it would be present at the time the information from that word position was utilized in reading.

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Insert Figure 2 about here

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To evaluate the accuracy of subjects' responses and the possibility of response biases, the pattern of responses in the experimental condition was compared to the pattern of responses in the no-switch control condition, where only one of the two critical words presented during the test was actually present in the text. In the no-switch control condition, subjects accurately selected only the critical word that was present 78% of the time, only the word not present 4% of the time, and both words 13% of the time (see the bottom of Figure 2). This indicates that the similarity between the two critical words did not greatly impair subjects' ability to choose the word

they actually saw. More of the errors are cases where subjects chose both words rather than only the incorrect word. Both words may sometimes have been chosen because the subject could not go back and change an earlier response. Note also that the frequency of choosing both words is much higher in the experimental than in the control condition, suggesting that subjects were often choosing both words in the experimental condition because they saw both words, not because they were uncertain. In general, the accuracy of responses in the no-switch control indicates that the effects in the experimental condition are not caused only by errors or response biases.

Turning now to the manner of utilization question, the results of this study do not allow a complete answer, but some hypotheses can be ruled out. First, the trend shown in the top of Figure 2, which is consistent with a variable crucial period hypothesis, is also consistent with a left-to-right scan or an initial-letter-first order of processing. A left-to-right serial letter scan hypothesis makes the other prediction that the word present early in the fixation should be more frequently reported when the fixation is to the right and the word present later in the fixation should be more frequently reported when the fixation is to the left of the critical letter, as explained earlier. There is no evidence of such a pattern in the actual data, shown in Figure 3. The probability of reporting a single word, be it the first or second word, is the same whether the fixation is to the left or to the right of the critical letter. These results do not support the serial letter scan hypothesis.



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Insert Figure 3 about here

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The hypothesis that the initial letters of words are utilized earlier than other letters predicts that the critical word present during the first part of the fixation should be reported more often in words having the first letter changing than in words having the fourth letter changing. However, the data do not show this pattern. The first word was selected alone 25% of the time when the first letter was changing and 33% of the time when the fourth letter was changing. Likewise, the second word was selected alone 37% of the time when the first letter was changing and 35% of the time when the fourth letter was changing. So there is very little difference in the pattern of single word responses for words having the first or fourth letter changing, and the small differences that exist are in the direction opposite that predicted by this hypothesis. Figure 4 presents the frequency of reporting the first, the second, and both words, in each mask onset time in the experimental condition, for each critical letter position. The patterns of responses for the two classes of words are very similar.

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Insert Figure 4 about here

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These data were analyzed as a three dimensional frequency table using the method of log-linear models (Bishop, Fienberg, & Holland, 1975; Everitt, 1977). The three variables in the table were mask onset time, critical letter

position and response, where response was classified as first or second word chosen; only single word responses were included in this analysis. Tests of partial association were computed for all the two-factor interactions and the three-factor interaction. Two of the three first order interactions were significant, the interaction between mask onset time and response ( $\chi^2$ (2) = 105.64, $p \sim 0$) and the interaction between response and critical letter position ( $\chi^2$ (1) = 4.52, $p$ = .03). There was no significant second order interaction between the variables ( $\chi^2$ (2) = 1.65, $p$ = .44). When each of the three possible models which contain the significant interaction terms are fitted to the data, the model containing only the mask onset time by response term (and all the lower order terms) was sufficient to explain the observed effects ( $\chi^2$ (6) = 7.98). The other two models did not provide a significantly improved fit. The differences in observed frequencies can be accounted for strictly on the basis of the effect of the mask onset manipulation on response. This effect is the same for the words having the first letter switching as for the words having the fourth letter switching. The data do not support the hypothesis that initial letters are processed before other letters of a word.

What Determines Which Word is Reported?

Further analyses were done in an attempt to identify some of the factors which determined whether subjects reported having seen the first, second, or both critical words. One factor is the length of time a word is present during a fixation. As discussed above, the trend shown in the top of Figure 2 indicates that the longer the first word is present, the more likely it is to



be reported and the less likely the second word is to be reported. A further analysis was done to see if this same effect can be observed for the duration of the second word. Unlike the duration of the first word, which was fixed by the mask onset time, the duration of the second word varied depending on the fixation duration. In order to determine the length of time the second word was present, it is necessary to identify the fixation on which the critical word was identified. McConkie, Zola, Blanchard, and Wolverton (1982) have shown that in cases where a five letter word is fixated only once, that fixation is typically the one which provides the visual information for the perception of that word. Therefore, instances were selected from the present data where there was only a single fixation on the critical word. This yielded 500 fixations, which were used to calculate the durations of the second words. Second word durations longer than 330 msec were excluded. The remaining durations were grouped into intervals of 30 msec each, and the probability of reporting the first word, the second word, and both words was calculated for fixations in each interval. This is presented in Figure 5. It is clear that as the duration of the second word increases, the likelihood of reporting the second word increases and the likelihood of reporting the first word decreases. The likelihood of reporting both words does not change systematically with the duration of the second word. The point biserial correlation between the second word durations and reporting the second word was .19 ($p$ = .001). The correlation between the second word durations and reporting the first word was -.25 ($p$ = .001). Although the second word was present for much longer times than the first word, the likelihood of reporting that word continued to increase even at very long durations.

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Insert Figure 5 about here

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The predictability of the critical word in its textual context is another factor which determines which word is reported. Predictability was ascertained through the norming questionnaire described earlier. The percentage of questionnaire subjects who guessed each word from its preceding context plus all the letters except the critical letter was used as a measure of the predictability of that word. The predictability of a word was significantly correlated with the percentage of responses where the word was chosen alone ($r$ = .43, $p$ < .01). There was also a significant correlation between predictability and the percentage of responses where the word was chosen alone given that the word was presented first in the fixation ($r$ = .38, $p$ < .01), and given that it was presented second in the fixation ($r$ = .30, $p$ < .01). The more predictable a word was, the more likely the word was to be reported, regardless of whether that word was the first or second word presented. In the control condition, there was a smaller correlation between the predictability of a word and the percentage of responses where the word was correctly identified as the only one that appeared in the text ($r$ = .19, $p$ < .01). In contrast, the predictability of a word did not correlate ($r$ = .00) with the percentage of responses where both words were chosen in the experimental condition.

A variable which did correlate significantly with the percentage of both-word responses was the visual similarity of the critical letter pair.



The measure of similarity was taken from Zola (1982, Table 3.2, p. 113). Zola, using the same equipment and type font as in this study, presented subjects with pairs of lower case letters and had them respond "same" or "different." The median latencies for a response of "different" was used as a measure of visual similarity for the critical letter pairs used here. The correlation between similarity and both-word responses was negative ($r$ = -.32, $p$ < .01) indicating that the more dissimilar the two critical words, the more likely it was that both words were reported. When letters were visually dissimilar, the display change may have been more noticeable and subjects' attention may have tended to be attracted to the change, causing then to see both words more often. Alternatively, it may be that when the visual system receives discrepant information about a word, it tends to construct a single, unified percept when the discrepancy is small, such as when the critical letters are highly similar, but when the discrepancy is large, a unified percept cannot be formed, so the subject becomes aware of the presence of two words during the fixation.

Effects on Eye Movements

First, the effects of briefly masking the text, independent of the switching letter manipulation, were determined by comparing the no-mask control condition to the no-switch control condition. Summary statistics for mask and no-mask data are presented in Table 1. Taking all fixation durations less than one second, the mean for the masked control condition is 20 msec longer than the mean for the no-mask condition ($t$ (10875) = 9.01, $p$ < .001). Readers also made shorter saccades and more fixations in the masked condition,

but there was no difference in the percentage or length of regressive saccades.

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Insert Table 1 about here

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Next, to determine the effect which the switching of the critical letter had on fixation durations, independent of the effects of the mask, the experimental condition was compared to the no-switch control condition. The fixation duration data were selected in four different ways. Prior to the selection process, fixations were excluded from the data set if they occurred during a disturbance in eyetracking, had durations longer than one second, were preceded by a regressive saccade, or were rereads, which are fixations preceded by a forward saccade but occurring when the eye has already fixated farther to the right on the current line. First, fixations which were the only fixation on the critical word were selected for analysis. This will be referred to as the single fixation data. These fixations are the most likely to have been the fixations on which the critical word was acquired (McConkie et al., 1982). However, because this selection procedure produced a small data set, a more liberal criterion was also used. This involved selecting fixations which were the first fixation on the critical word. The first fixation could be the only fixation on the word or there could be several refixations of the word after the first fixation. The first fixation data contains more fixations on which information from the critical word was acquired, but it also may contain a larger percentage of fixations on which



the critical word was not acquired. Next, those fixations which immediately preceded fixations defined as the first fixation were selected for analysis. This will be referred to as the prior fixation data. And finally, those fixations which immediately followed first fixations, whether they were on the critical word or not, were selected for analysis. This will be referred to as the following fixation data. Most fixations on which the critical word was acquired should have been included in one of these last three categories. Analyses of variance were done on means calculated from the raw data for each cell in a matrix defined by the crossing of all factors with the subject factor, in order to alleviate problems with the unbalanced design and to equalize each subject's contribution to the data.

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Insert Table 2 about here

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The mean fixation durations in the experimental and no-switch control conditions for each of the four data sets are presented in Table 2. A repeated measures analysis of variance was performed on fixation durations for each of these data sets. The factors were Condition, Mask Onset Time, and Critical Letter Position (first or fourth letter). Although there was no switching letter in the no-switch control, the data can be classified on this factor since the single word that was present belonged to a group differing in either the first or fourth letter. Mean fixation durations were longer in the experimental condition than in the control for the first fixations ($F$ (1,15) = 7.05, $p$ = .02), and the single fixations ($F$ (1,15) = 16.89, $p$ ~ 0). The

following fixation data showed the same pattern, but did not reach significance ($F$ (1,15) = 1.56, $p$ = .23). The prior fixation data showed the opposite effect, with the experimental conditions being shorter than the control ($F$ (1,15) = 7.51, $p$ = .02). It may be that the switching letter is sometimes noticed in the periphery on fixations prior to the fixation on which the word is identified. The perceived movement may cause attention to be drawn to the critical word, so the prior fixation is terminated early and the next fixation is sent to the critical word. Further research is needed to investigate this phenomenon.

The only other significant effect was the Condition X Mask Onset Time interaction in the analysis of single fixations, $F$ (2,30) = 3.56, $p$ = .04. This suggests a differential effect of mask onset in the experimental and control conditions, but the data pattern do not suggest any clear interpretation.

The frequency of regressive saccades in the two conditions was also examined. The percentage of regressive saccades initiated within 5 character positions to the left or right of the critical letter position is 21% in the no-switch control condition and 30% in the experimental condition. Also, fixations following regressive eye movements are 23 msec longer in the experimental conditions than similar fixations in the control conditions, a significant difference ($F$ (1,15) = 8.85, $p$ = .01).

In summary, the presence of a mask inflated fixation durations by 20 msec, and the occurrence of a letter change increased the durations of the fixations on which the words were perceived by another 23 msec. The duration



of the prior fixation was reduced by 11 msec.

Eye Movement Effects Associated with Type of Response

The fixation duration data for the experimental condition were classified according to the type of response made to the corresponding test items. The means for the prior, first, following, and single fixation data are presented in Table 3 along with the means for all responses in the no-switch control condition. These means were compared to means for the experimental data grouped into two response categories: reporting only one word and reporting both words. A one-way repeated measures analysis of variance was done on the raw data with this three level Type of Response factor. The mean fixation durations for the single-word, both-word, and control (all response types) groups were not significantly different in the prior fixation data, $F$ (2,28) = 1.74, $p$ = .19, or in the following fixation data, $F$ (2,28) = 0.85, $p$ = .44. The means were significantly different in the first fixation data, $F$ (2,28) = 7.40, $p$ ~ 0, and in the single fixation data, $F$ (3,45) = 7.18, $p$ ~ 0. Multiple comparisons for each possible pair of means were performed using the Bonferroni $t$ statistic. For the analysis of first fixations, the critical value of $t$ was 2.55 using a .05 level of significance (two-tailed). The both-word mean was significantly different from the control mean and the single-word mean, but the control and single-word means, however, were not significantly different. For the single fixation data, the critical value of $t$ was 2.76, using the .05 level, and the pattern of significance of the pairwise contrasts was identical to the pattern in the first fixation data. It appears that the inflation of fixation duration caused by the switching

letter manipulation is limited to cases where the subject reported seeing both critical words. This suggests that there may be no disruptive effects of the switching letter when only one word is perceived.

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Insert Table 3 about here

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An analysis was also done with the single-word response category separated into first-word-only and second-word-only responses, i.e. a four level Type of Response factor. The means for the first-word-only and second-word-only responses in the first and single fixation data are presented in Table 4. The first-word-only mean is shorter than the control mean (refer to Table 3), whereas the second-word-only mean shows a substantial inflation relative to the control, comparable to the inflation in the both-word mean. In the pairwise contrasts, done in the same way as above, the second-word-only mean was significantly different from the control, in both the first and single fixation data, while the first-word-only mean was not significantly different. This difference between the first-word-only and second-word-only means is expected because of selection effects. On shorter fixations, the first word is likely to be present for the most time, and on longer fixations, the second word is likely to be present for the most time. Since the longer a word is present, the more likely it is to be reported, this means that partitioning fixations on the basis of which word was seen will result in a fixation duration difference of the type observed.



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Insert Table 4 about here

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## Discussion

The results are consistent with the variable crucial period hypothesis. Subjects often reported a single word, suggesting that they were utilizing information that was available at some specific time during the fixation. Subjects did not consistently report seeing the first or the second word, suggesting that this crucial period occurs at different times during different fixations. Further evidence for this hypothesis is found in the fixation duration data: when subjects reported seeing a single word, the durations of their fixations were similar to those of the control group, providing no evidence of a disruptive influence resulting from having two words present on a single fixation. There do not appear to be effects on fixation duration which could be ascribed to unconscious recognition of the unreported word. This is quite different from the case where subjects reported seeing both words. When that happened, the fixation durations were increased substantially, suggesting a disruption of the normal reading process. Perceiving two words during a fixation clearly had different consequences on reading than did perceiving only one, which was apparently the more frequent case.

The variable crucial period hypothesis can also account for the finding that the longer a word is present on the screen the more likely it is to be reported. Since utilization is assumed to take place at some specific time

during the fixation, the likelihood that a given word will be present at that time varies directly with the length of time that the word is present. In asking why it is that a given word is utilized at one time rather than another during the fixation, it seems likely that this is based on language processing. The information provided by a word is brought into play in the ongoing reading process when it is needed to advance the comprehension of the text.

There are also several ways in which the variable crucial period hypothesis can account for cases where both words were reported. First, it may be that on occasions a word was attended at two different times during a fixation. Second, it may be that sometimes a word was attended during the period in which the display change took place, so both words were seen. Finally, the mask might have failed sometimes to direct attention away from the critical letter position, allowing the changing letter to be detected on the basis of localized movement.

The results provided no evidence for a left-to-right sequence in utilizing different parts of the text or for the initial letter of a word being acquired prior to other letters. A left-to-right serial scan of letters, syllables, or letter groups predicted that the likelihood of reporting the first and second word should differ with the position of the fixation relative to the critical letter. Instead, the likelihood of report was the same across fixation position. The hypothesis that initial letters of words are utilized first predicted that the trend in reporting single words across mask onset time would differ depending on whether the first or the



fourth letter was being changed. No such difference was found.

Another factor that influenced the likelihood of reporting a word was its contextual predictability. Predictability could have its influence at perception or during the process of making a response. For several reasons, it seems likely that the influence of predictability in the experimental condition is not completely explainable by response processes. Subjects might have chosen the more predictable words from the critical word pairs shown at test because the more predictable words had a stronger connection to the text. If a guessing bias such as this had occurred, it should have equally effected the responses in the no-switch control and experimental conditions. However, the magnitude of the correlation was smaller in the control condition, suggesting that, although response effects may be completely responsible for the influence of predictability in the control condition, a combination of perceptual and response effects are responsible for the influence of predictability in the experimental condition. It could also be argued that subjects were deliberately choosing one word in the experimental condition because of demand characteristics in the experiment, that is, they might have deliberately chosen the more predictable word, even though they actually saw two words. Although, if this were the case, a higher correlation would be expected in the experimental condition, the demand characteristics explanation is inadequate for other reasons. Subjects were completely informed of the manipulation, and were told that they could report both words. And, in fact, on a third of all the responses, subjects reported seeing both words, and each subject did report both words sometimes. If demand characteristics were at all a factor, they could not have been very important.

Predictability, therefore, seems to be influencing which critical word is utilized in the experimental condition. One way in which this might occur is through predictability speeding the perception of words (Tulving & Gold, 1963). Morton (1969), for instance, suggests that the activation level of logogens for more predictable words are raised, so that the threshold for perception of the word is reached more quickly by the additional activity resulting from the visual pattern of the word. If this were the basis for the predictability effect observed here, then the correlation between the predictability of a word and its being reported should be particularly high for the initial words when presented for only 50 msec. This correlation should drop when the initial word is present for longer periods of time, because at the longer times low predictability words should be perceived as well as high predictability words. An examination of these correlations shows exactly the opposite pattern. The correlation between predictability and the percent of time the initial word is reported is .02 when it is present for 50 msec, .28 ($p < .01$) when present for 80 msec, and .39 ($p < .01$) for 120 msec. Thus, the data do not support the hypothesis, and are counter to what would be expected from the logogen model. If predictability is influencing perception, it must be doing so in some manner other than by determining the speed of perception.

The effect of predictability can be explained within the frameworks of an interactive theory of reading (Rumelhart, 1977) or theories involving production systems (e.g. Just & Carpenter, 1980). These theories share a common feature: higher level processing essential to the comprehension of the text responds not only to the presence of encodings driven by visual input,



but also to other information available from previously read text, and to prior knowledge about language regularities, characteristics of texts, and characteristics of the world. At the moment when such higher level processing occurs an information configuration exists which includes both visually provided elements and elements from previous knowledge. These theories which assume that a certain source of information is brought into play only at a certain time, with that time dependent upon other aspects of the cognitive configuration, also include an implicit assumption of the variable crucial period hypothesis. Perhaps it would be more appropriate, in these cases, to speak of such theories as including the assumption of a Variable Utilization Time Principle; that is, information is used at a specific time which is determined, in part, by factors other than the presence of that information.

Theories which include the assumptions described above can account for both the effect of predictability and the evidence for a variable crucial period in the following way. At the beginning of a fixation one word becomes present to the system. Partway through the fixation there is a mask, which is not assumed to erase the previously presented pattern, but only to overlay it with an additional configuration (cf. Eriksen & Schultz, 1978). Thirty msec later a third pattern appears, the same as the first but with one letter changed. Again this adds to the visual configuration present. The presence of two words in the same location is likely to result in a stimulus configuration which may not be completely determinate. Depending on when the crucial period occurs, that is, when the information from that word position is brought into play in higher levels of processing, the visual information may clearly specify one word or may provide conflicting information. If the

crucial period occurs early in the fixation, before the second word has appeared, the visual configuration will be completely determinate for the first word. Late in the fixation, when the second word is present, information from the first pattern has faded, making the visual configuration determinate for the second word. If the crucial period occurs soon after the mask and the onset of the second word, the visual configuration will include conflicting information from the first and second words. With conflicting information, either of two things might happen. If the two patterns are quite discrepant, the reader may become aware of two words. Where the two patterns are less discrepant, the decision concerning the word present may be strongly influenced by non-visual information sources, given the fact that the visually provided information is less determinate than usual. In this situation, language constraints and contextual factors play a greater than normal role in determining which word is perceived, thus producing the observed effect of predictability. Obviously, for this explanation to hold, we must assume that the added processing time required in selecting a reading for a word, when this reading is more heavily determined by contextual factors than is normally the case, must be minimal. Otherwise, we would expect to see effects on the fixation durations which in fact were not found.

This study suggests two theoretical constructs that should be included in theories of reading. The first is the Variable Utilization Time Principle, as a basic principle in the use of visual information during reading. Second is the assumption that the processes involved in reading can be divided into two sets; those that are driven directly by the stimulus configuration on the retina, and those that are involved in the comprehension of the language. The



first set provides a representation, at some presently unknown level, of the visually provided information, and the second can be influenced by that information. However, the time of this influence is not determined by when the visually provided information becomes available.

There are situations outside the domain of normal reading in which the second set of processes are set to respond to the visual information as soon as it becomes available. Identifying words from tachistoscopic presentation would be a prime example of this. If no contextual constraint is provided, no action can be taken toward accomplishing the task until the visual information becomes available. Cognitive processes in such tasks can be thought of as being driven rather directly by the visual stimulus, and their timing characteristics can be measured with respect to the onset of that stimulus. In more complex tasks like reading, however, higher-level cognitive activities are on-going, and the time of utilization of the visually provided information depends on when the system is in an appropriate state to respond to it. This suggests that it is inappropriate to think of a fixation in reading as analogous to a tachistoscopic presentation, as has been so common in reading research. It also clarifies the relation between tachistoscopic research and reading research. There are undoubtedly certain processing characteristics that are common to a person's response to a tachistoscopic presentation, and to a fixation made during reading. The characteristics in common will be those that are automatically produced in response to retinal stimulation, those by which visual information is provided to the system. However, at the present time we do not know how far this automatic processing proceeds. Whether it results in the latent arousal of word meanings, or only in the

arousal of some letter or word level codes, must be a matter for future research. Finding the answer to this question will help us to know what aspects of the vast literature of tachistoscopic research using letters and words is likely to be applicable to understanding the nature of the processing taking place during a fixation in reading.



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Table 1

Summary Statistics for All Eye Movement Data

in the Control Conditions

| Fixation Duration | | | Median Forward Saccade Length | Median Regressive Saccade Length | Percentage of Regressive Saccades | Average Number of Fixations per Line |
|---|---|---|---|---|---|---|
| N | Mean | S.D. | | | | |
| No-mask Control | | | | | | |
| 6568 | 245 | 113 | 8 | 5 | 23 | 10 |
| No-switch Control | | | | | | |
| 4309 | 265 | 120 | 7 | 5 | 22 | 11 |

Note. Fixation durations are given in milliseconds. Saccade lengths are given in number of character positions; 4 character positions = 1 degree of visual angle.

Table 2

Summary Statistics for Fixation Durations

| | Condition | | | | | |
|---|---|---|---|---|---|---|
| | No-Switch Control | | | Experimental | | |
| | N | Mean | S.D. | N | Mean | S.D. |
| Prior Fixation Data | 341 | 263 | 89 | 968 | 252 | 81 |
| First Fixation Data | 358 | 282 | 86 | 1035 | 296 | 117 |
| Following Fixation Data | 289 | 268 | 91 | 826 | 279 | 113 |
| Single Fixation Data | 221 | 287 | 78 | 498 | 310 | 114 |

Table 3

Average Durations of Fixations in the Region of the Critical Word Classified by Condition and by Type of Response on the Test

| Condition and Type of Response | | Prior Fixation | First Fixation | Following Fixation | Single Fixation |
|---|---|---|---|---|---|
| No-switch Control | | | | | |
| | Mean | 263 | 282[a] | 268 | 287[a] |
| | S.D. | 89 | 86 | 91 | 78 |
| | N | (341) | (358) | (289) | (221) |
| Experimental | | | | | |
| Single Word | Mean | 254 | 291[b] | 280 | 303[b] |
| | S.D. | 81 | 108 | 110 | 102 |
| | N | (619) | (673) | (538) | (371) |
| Both Words | Mean | 250 | 313[ab] | 276 | 337[ab] |
| | S.D. | 83 | 132 | 121 | 150 |
| | N | (320) | (330) | (261) | (107) |

Note. Means in a column which have a superscript letter in common are significantly different ($p < .05$).

Table 4

Average Durations of Fixations on the Critical Word for Single Word Responses in the Experimental Condition

| Type of Response | | First Fixation | Single Fixation |
|---|---|---|---|
| First Word Only | Mean | 259 | 269 |
| | S.D. | 86 | 88 |
| | N | (294) | (156) |
| Second Word Only | Mean | 315* | 327* |
| | S.D. | 117 | 106 |
| | N | (379) | (215) |

* Significantly different form the mean for the no-switch control condition ($p < .05$ ).

## Figure Captions

Figure 1. Example of the sequence of displays given to the subject in the experimental condition.

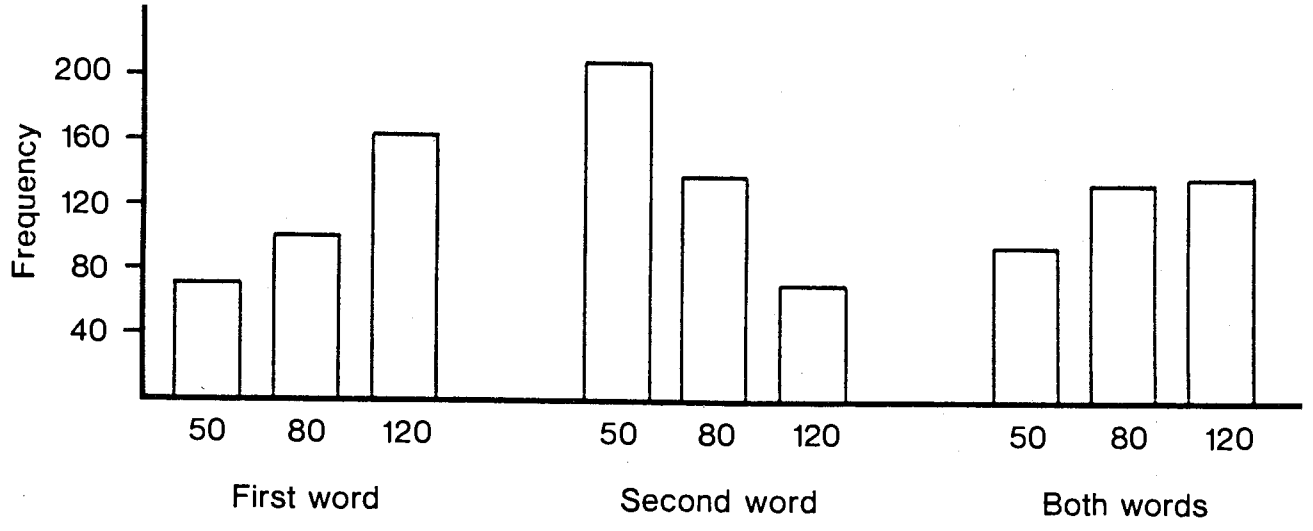
Figure 2. The frequency of reporting one or both of the critical words at test in the 50, 80, and 120 msec mask onset times of the experimental and no-switch control conditions.

Figure 3. The percentage of responses on which only the first or second presented word was chosen when the fixations are centered to the left or right of the critical letter position. Eyeposition values indicate the number of character positions away from the critical letter position, where negative values are to the left of the critical letter.

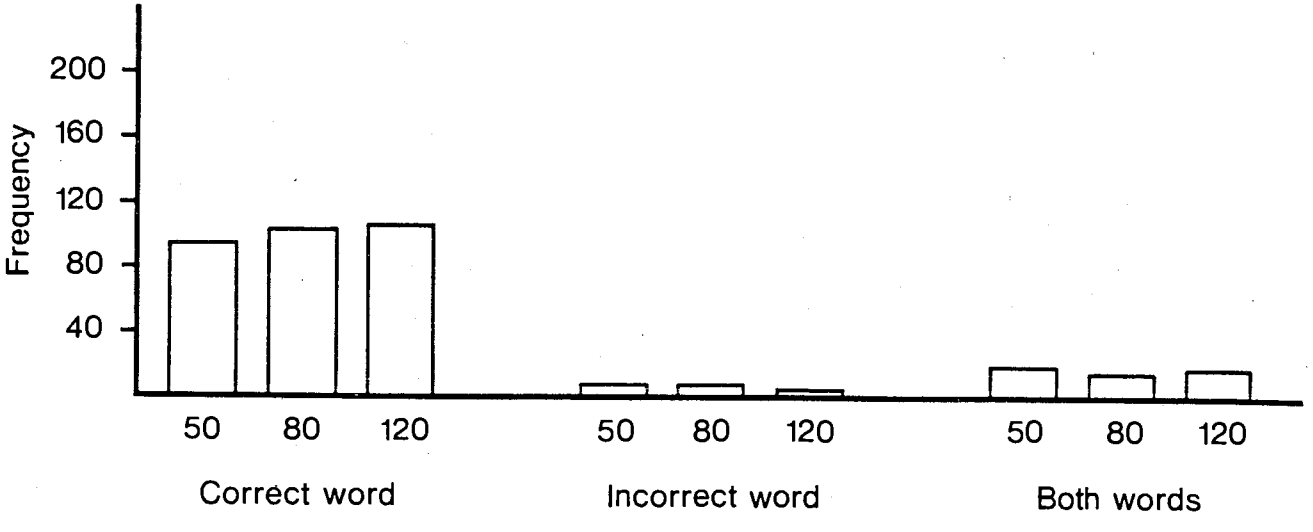
Figure 4. The frequency of reporting one or both of the critical words at test in the 50, 80, and 120 msec mask onset times of the experimental condition when the critical letter is the first or fourth letter of the critical word.

Figure 5. Probability of reporting one or both of the critical words at test for 30 msec intervals of the duration of the second word during fixations which were the only fixations on the critical word in the experimental condition.

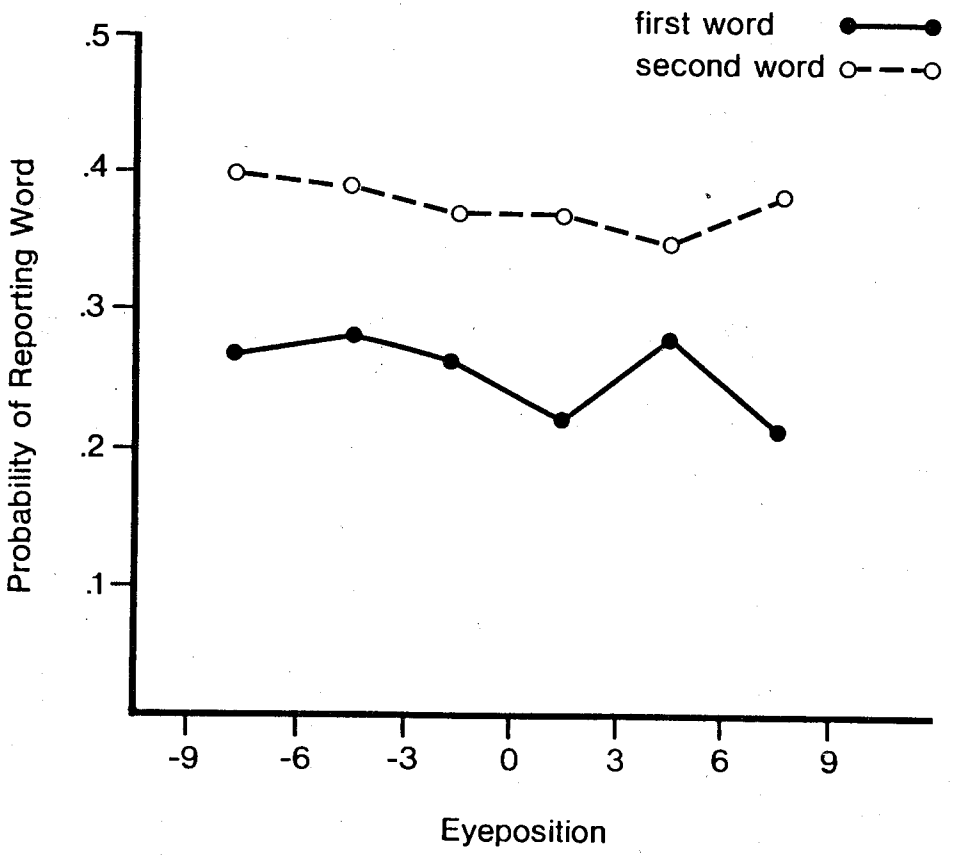
| Elapsed Time (msec.) Condition 1 | 2 | 3 | Display |
|---|---|---|---|
| 0 | 0 | 0 | The underground caverns were meant to house hidden tombs, but then the |
| 50 | 80 | 120 | XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX |
| 80 | 110 | 150 | The underground caverns were meant to house hidden bombs, but then the |

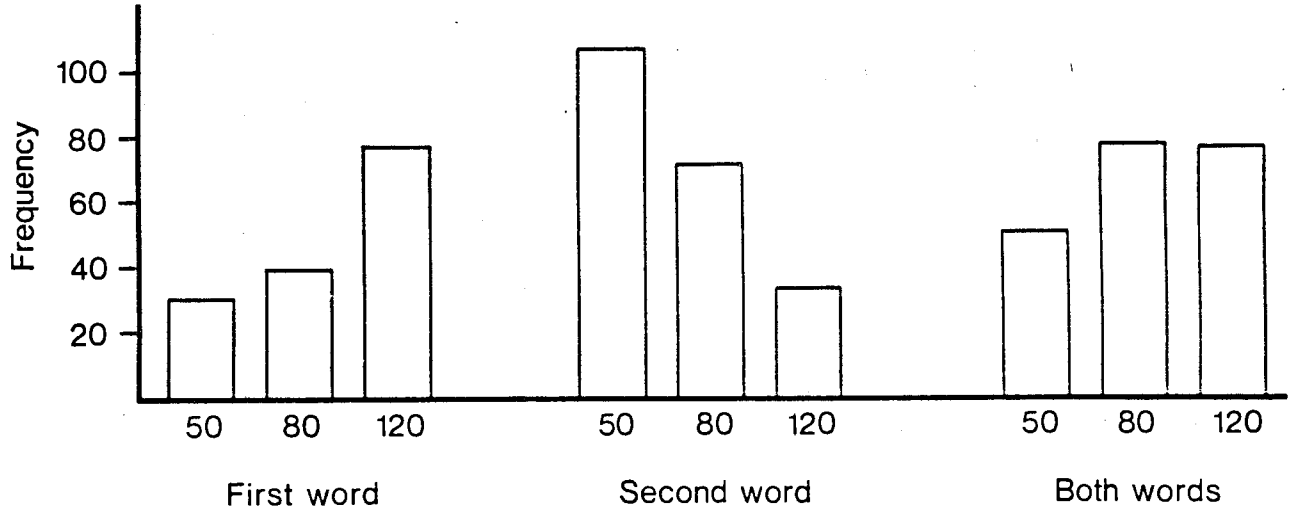



EXPERIMENTAL CONDITION

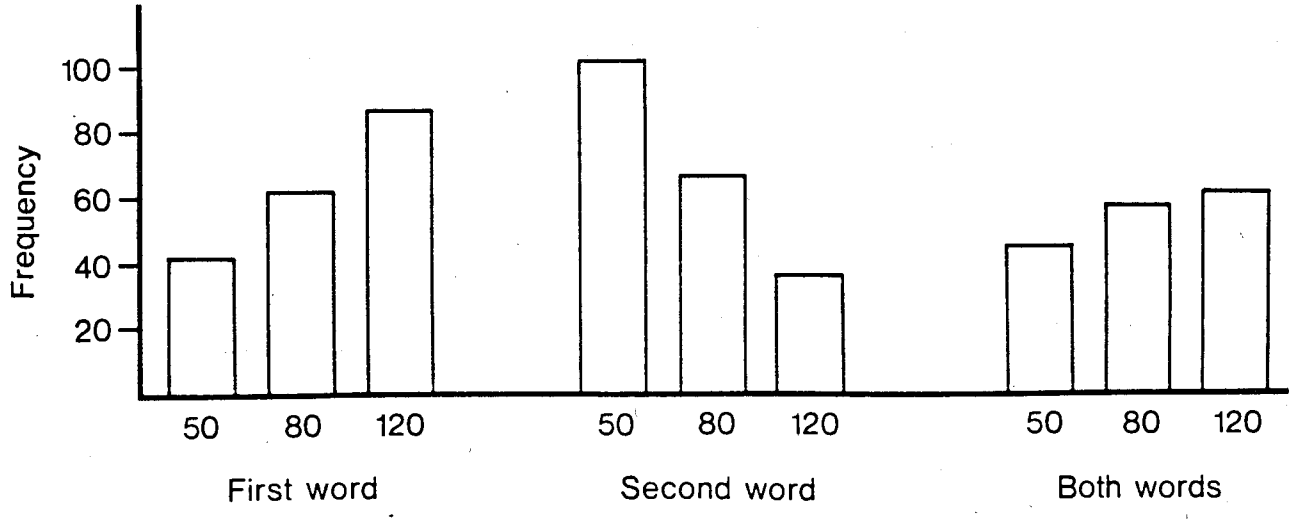



CONTROL CONDITION

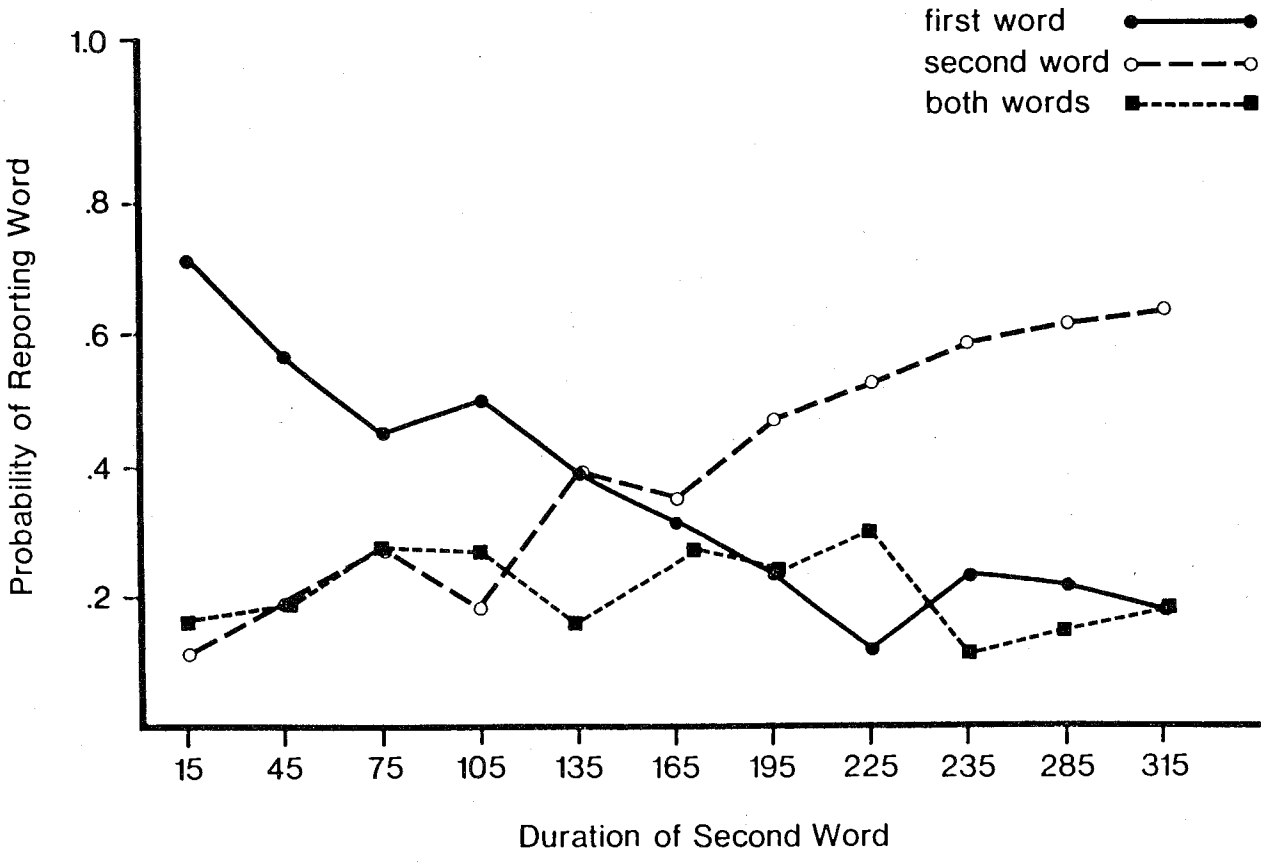

first word
second word
.5
.4
.3
.2
.1
Probability of Reporting Word
-9
-6
-3
0
3
6
9
Eyeposition




FIRST LETTER SWITCHING




FOURTH LETTER SWITCHING


first word
second word
both words
1.0
.8
.6
.4
.2
Probability of Reporting Word
15
45
75
105
135
165
195
225
235
285
315
Duration of Second Word