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ABSTRACT

Fourteen college students read passages displayed on a cathode-ray tube as their eye movements were monitored in a study that examined (1) whether letters that lie in the center of vision are used earlier in the fixation than letters further to the right, (2) how soon after a stimulus event that event can affect eye movement control, and (3) how soon in a fixation the presence of an orthographically inappropriate letter string can be shown to influence eye movement decisions. During occasional fixations, all letters to the left of the directly fixated letter or all letters more than four to the right of the fixated letter were replaced by other letters. This replacement occurred either for only the first ms. of the fixation or only after the first 100 ms. of the fixation. The eye movement data indicated that the eyes can respond to change in the visual stimulus within less than 100 ms., and to orthographic irregularity in the text within less than 160 ms. No evidence was found for a left-to-right attentional scan during a fixation. The findings suggest that the response time of the eyes is shorter than usually proposed in theories of visual processing, and that eye movement decisions are made later in the fixation than has often been assumed. In addition, they show that much of the processing takes place too late to affect the immediately following saccade and hence is revealed only later in the eye movement pattern. Thirty-six references are listed. (Author/FL)

CENTER FOR THE STUDY OF READING

Technical Report No. 331

# SOME TEMPORAL CHARACTERISTICS OF PROCESSING DURING READING

G. W. McConkie, N. R. Underwood,
D. Zola, and G. S. Wolverton

University of Illinois at Urbana-Champaign

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University of Illinois
at Urbana-Champaign
51 Gerty Drive
Champaign, Illinois 61820

Bolt Beranek and Newman Inc.
10 Moulton Street
Cambridge, Massachusetts 02238



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## Abstract

College students read passages displayed on a cathode-ray tube as their eye movements were being monitored. During occasional fixations all letters to the left of the directly fixated letter or all letters more than four to the right of the fixated letter were replaced by other letters. This replacement occurred either for only the first 100 ms of the fixation or only after the first 100 ms of the fixation. The eye movement data indicated that the eyes can respond to change in the visual stimulus within less than 100 ms, and to orthographic irregularity in the text within less than 160 ms. No evidence was found for a left-to-right attentional scan during a fixation. The results were interpreted within the framework of a chronology of processing events occurring during a fixation in reading.

# Some Temporal Characteristics of Processing During Reading

The purpose of this article is to explore some temporal characteristics of the perceptual processing that takes place during fixations in reading. The literature contains many speculations, and some evidence, about the chronology of processing events that may be taking place during a fixation as a person reads. For present purposes, the chronological issues are grouped into three sets of questions: (a) questions regarding the relative time of various processing events, (b) questions regarding the absolute time of certain processing events, and (c) questions regarding whether certain processing events occur sufficiently early to affect when the present fixation will terminate and/or where the eyes will be sent for the next fixation. Our general approach to investigating these issues is to focus on when it is that different aspects of the textual stimulus perceived during a fixation are employed in the reading process. This requires that particular aspects of the stimulus be modified as a person reads, and then a determination be made of when, in either relative or absolute terms, these aspects of the stimulus have their effects on the processing involved.

## Relative Times at Which Stimulus Information is Used

There have been many proposals suggesting that certain types of processing take place prior to others during fixations in reading. One widely discussed controversy has focused on whether processing during reading follows a bottom-up (Gough, 1972), top-down (Goodman, 1976), or interactive (Rumelhart, 1977) sequence. One aspect of this controversy concerns whether lower level perceptual processes precede or follow the higher level, more cognitive processes or whether processing at different levels occurs simultaneously with influences passing in both directions.

Another proposal suggests that there is a sequence in the time at which different parts of the text perceived during a fixation are attended or encountered. For instance, a left-to-right scan of the letters during a fixation has been proposed (Gough, 1972), with the added assumption that this "read-in" of the stimulus occurs at a rate of approximately 10 ms per letter (Geyer, 1966). Such a serial consideration of the text elements might also be part of a phonetic encoding of the text. An attentional scan might also occur in a more flexible manner. For instance, the scan might function within a fixation with larger units, perhaps common letter clusters, syllables or even words. In this case, each such unit would be used as it is needed for the ongoing language processing (McConkie, 1979).

Other proposals have not included a serial input or attention scan notion, but have proposed other bases for the use of different information at different times during a fixation. For instance, foveal and near foveal information may be used early in the fixation for word identification, with more peripheral information being used only later as decisions about where to send the eyes are being made (Rayner, Inhoff, Morrison, Slowiaczek, & Bertera, 1981). Or peripheral information may be used early in the fixation for determining where to send the eyes next, allowing enough time for the motor program to be executed (Rayner, 1983). Or peripheral information may be sufficiently slow in reaching the brain that it arrives only at the time when corresponding information from the fovea arrives during the next fixation, with these two sources of information reinforcing each other in the word identification process (Bouma, 1978). Finally, it is possible that there is a sequence in which lower spatial frequency aspects of the text stimulus are obtained and have their influence slightly earlier in the fixation than do higher frequency aspects, either because transmission rates vary for different spatial frequencies (Breitmeyer & Ganz, 1977) or because more fine-grained aspects of the stimulus pattern require a longer period of energy integration on the retina before becoming available (Eriksen & Schultz, 1978). Of course, these latter factors are likely to produce relatively small differences in processing times.

## Absolute Times at Which Stimulus Information is Used

In addition to general considerations concerning the relative times during a fixation at which different types of processes occur, there have been suggestions of specific intervals within a fixation during which particular events occur. The first such suggestion concerned the existence of a saccadic suppression period during the early part of each fixation, following the saccade, and during the latter part, just prior to the subsequent saccade (Haber & Hershenson, 1973). Although it has been well demonstrated that these are periods during which the visual sensitivity threshold is raised somewhat, it appears doubtful that this is of much significance for the reading of high contrast textual stimuli (Rayner, Inhoff, Morrison, Slowiaczek, & Bertera, 1981; Salthouse & Ellis, 1980; Wolverton, 1979). Stimuli present during these periods clearly affect visual processing and can frequently be reported. Another proposal is that the first 50 ms of each fixation is the time in which visual information is acquired from the text, with the remaining time being used for other aspects of processing (Rayner, Inhoff, Morrison, Slowiaczek, & Bertera, 1981). This presumably corresponds to Just and Carpenter's (1980) first stage of processing labeled get next input.

Of particular importance in putting such proposals into perspective is a consideration of transmission periods, as summarized by Russo (1978; see also McConkie, 1983). Neurophysiological studies indicate that the time required for retinal stimulation to begin to affect the visual cortex is about 60 ms. Furthermore, the time required for electrical stimulation of the appropriate region of the motor cortex to cause the eyes to begin to move is about 30 ms. These facts place important constraints on other considerations of the temporal characteristics of processing during fixations, as can be seen in Figure 1. This figure presents a schematic representation of two successive fixations. We will consider events associated with the first of these fixations, which is assumed to be 220 ms in duration, about average for fixations in reading. In discussing these events, we will employ the common distinction of central versus peripheral neural activity. Central events are those that take place within the brain, and peripheral events include retinal stimulation and characteristics of eye movements. Two peripheral events mark the beginning and ending of the fixation. These are labeled <u>saccade termination</u> and <u>saccade onset</u>. Central events are based on the transmission time information discussed above. One event, labeled <u>information available</u>, is the point at which the visual stimulus present on this fixation begins to affect neural activity of the cortex. Another is the point at which the command to move the eyes is sent, here labeled the <u>point of no return</u>. It is assumed that processing following this point of no return occurs too late to have any effect on the time at which the following eye movement will occur; thus it is too late to affect the duration of that fixation. A third central event is the point at which the retinal smear resulting from the beginning of the saccade reaches the cortex, thus providing a new stimulus pattern that begins to interfere with and replace the neural activity pattern resulting from the stimulus present on the prior fixation. This is assumed to occur 60 ms following the onset of the saccade; this reflects the neural transmission time and is labeled the <u>movement-induced interference</u>. Finally, the point at which the stimulus pattern from the following fixation begins to have its effect on the visual cortex, occurring 60 ms after the completion of the saccade, is again labeled <u>information available</u> and marks the beginning of the new cycle associated with the next fixation. Two additional events included in the figure are discussed later. If the times of these brain-level events are accurate, this conceptualization has important implications for further considerations of the temporal characteristics of processing events during fixations, particularly as they relate to the control of eye movements.

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Insert Figure 1 about here

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Temporal Factors in Eye Movement Control

The brain-level events described in the last section can be used to define critical processing periods. The first is the period during which the visual cortex is stimulated by the text pattern present during that fixation. This is a period of about the same duration as that of the fixation, 220 ms in the example, but offset by 60 ms. This is referred to as the brain-level stimulation period in Figure 1. The second period, a subset of the first, is that part of the brain-level stimulation period that lies prior to the point of no return, in this case 130 ms. This is the period of time during which processing activities can have an influence on how long the eyes remain at that location, and perhaps where the eyes go next. Its duration depends, of course, on the duration of the fixation itself. In the case of a 90-ms fixation, this period is of zero duration, suggesting that the durations of short fixations are not affected at all by the visual stimulus pattern present during those fixations. How long a fixation must be in order to be affected by the stimulus pattern is a matter of some interest in understanding eye movement control.

The next period of interest is that part of the brain-level stimulation period that follows the point of no return. This period, by the above assumptions, is a constant 90 ms period, regardless of the duration of the fixation. During this period, the brain is stimulated by the text pattern just as it was prior to the point of no return, but processing activities taking place are too late to have any influence on when the fixation terminates. This suggests that as the eyes are moving during the following saccade, and for the initial period of the following fixation, the brain is still being directly stimulated by the stimulus pattern present during the prior fixation.

In attempts to obtain a measure of the time required to process the information perceived during a fixation, it has sometimes been assumed that all this processing is completed by the time the decision is made to move the eyes to the next location (Just & Carpenter, 1980; McConkie, 1979; McConkie, Hogaboam, Wolverton, Zola, & Lucas, 1979). Under this assumption, the fixation time is then used as a measure of the processing time required. This approach is flawed in two ways. First, the time between the arrival of the retinal information at the brain and the point of no return, which is the actual processing time by the above assumptions, is 90 ms less than the duration of the fixation. Second, the assumptions stated above require that the period from the point of no return until the time when the brain is stimulated by the visual pattern present on the next fixation must be a dead time, in which no processing occurs (Russo, 1978). In the present example this consists of the 90 ms period following the point of no return, and a period during which the brain receives the stimulation pattern present during the saccade, which in reading averages about 35 ms. Together these constitute a 125 ms period, almost equal to the 130 ms period prior to the point of no return. To assume that this is dead time would suggest that during reading the mind spends only half its time in processing activities. This assumption does not seem tenable, either with respect to the conscious experience of processing continuity or with the requirements for an efficient processing system. Thus, these considerations indicate that the amount of time the eyes spend in a fixation on some text region is not likely to correspond in a simple manner to the time spent processing that region, though some more complex relationship probably exists.

Other discussions of whether the eyes are controlled in a manner tightly or loosely related to the cognitive processes taking place have also focused on considerations of the temporal characteristics of processing during fixations. Arguments for loose control generally suggest that the duration of the average fixation is too short to permit the reader to recognize foveal and peripheral information, make a decision on the basis of that information concerning where to send the eyes, and then to set up the proper motor sequence of commands necessary for the execution of the next movement (Bouma & deVoogd, 1974; Shebilske, 1975). This argument is buttressed by the fact that the reaction time of the eyes tends to be about 175-225 ms (Arnold & Tinker, 1939; Salthouse & Ellis, 1980; Westheimer, 1954). Proponents of a tight control of eye movements must show that processing of information to the levels assumed to be involved in this control occurs prior to the point of no return. For instance, Rayner (1983) argued for tight control by claiming that the visual information used to determine the time and extent of an eye movement is obtained during the initial 50 ms of a fixation, thus leaving sufficient time for the decisions to be made to influence the subsequent saccade, a time that was estimated to be about 175 ms. Our preceding analysis casts doubt on these time estimates but does not conflict with the possibility that fixations are influenced, at least at times, by information perceived on those fixations.

There is ample evidence that information available during a fixation can influence the duration of that fixation and the length of the immediately following saccade. However, the most compelling evidence presently available for this claim has shown immediate effects of errors and masked letters in the text (see McConkie, 1983, for a review). Examples of language factors producing an immediate effect on the eye movements comes from studies that are less well controlled.

## The Present Study

The purpose of the present study was to contribute further knowledge concerning the temporal characteristics of the processing taking place during fixations in reading. It was designed to provide evidence on three issues. First, are letters that lie in the center of vision used earlier in the fixation than letters further to the right? Second, how soon following a stimulus event can that event have an affect on eye movement control? (The above considerations suggest that this should require at least 90 ms but not over 175 ms.) Third, how soon in a fixation can the presence of an orthographically inappropriate letter string be shown to influence eye movement decisions? (Using this point, we can estimate how much time elapses from the time the stimulus pattern reaches the visual cortex until the time that orthographic characteristics of the text are being considered.) Answers to these questions would place further constraints on the chronology of mental processes occurring during a fixation in reading.

Therefore, on selected fixations during reading, letters in certain regions of the text, defined with respect to the directly fixated letter, were replaced by other letters. Two letter replacement regions were used: all letters to the left of the directly fixated letter or all letters more than four to the right of the fixated letter. The time of this replacement was also varied. On some fixations, the errors were present at the beginning of the fixation and were then replaced by the original letters after 100 ms, providing a normal text pattern during the latter part of the fixation. On others, the letter replacement took place only after the initial 100 ms of the fixation, resulting in normal text during the first part of the fixation and erroneous letters in the letter replacement region during the latter part. Crossing the two letter replacement regions with the two timing conditions resulted in four experimental conditions. A control condition was also included in which no errors were present. It was assumed that if foveal-central letters are used early in the fixation, and letters further to the right only later, then errors lying to the left of the directly fixated letter would have their greatest effect if they were present early in the fixation, whereas letters further to the right would have their greatest effect if they were present during the latter part of the fixation. Furthermore, the design permitted an analysis of how soon effects would be observed from the stimulus change that occurred in the middle of the fixation and how soon the effects of the presence of erroneous letters at the beginning of the fixation could be observed.

## Method

### Subjects

Fourteen college students served as subjects for this study. They had normal uncorrected vision, were native English speakers, and did not show facial structures that made it difficult to monitor eye movements. They had participated in other eye movement studies and were accustomed to reading in our laboratory setting.

### Apparatus

The text was displayed, one line at a time, on a computer controlled cathode-ray tube or CRT (Digital Equipment Corporation Model VT-11) having upper- and lower-case characters produced by a hardware character generator, using P-31 phosphor, which decays to 1% of original intensity in 500 microsec, and being interfaced with a PDP-11/40 computer. Pressing a button called the next line of text onto the CRT, permitting subjects to read multiline passages without difficulty. The line of text was refreshed every 3 ms and the entire line could be changed in the period of a single refresh cycle. The CRT was 48 cm from the subject's eyes, with three letter positions subtending one degree of visual angle.

Eye movements were monitored using a modified Biometrics Model SC limbus reflection eye movement monitor (Young & Sheena, 1975) which was also interfaced with the computer. The computer sampled the horizontal component of the eye position signal every millisecond. The computer program used in conducting the research was developed to permit the computer to produce changes in the line of text contingent on aspects of the reader's eye movement pattern. A more complete description of this system is given elsewhere (McConkie, Zola, Wolverton, & Burns, 1978).

Materials

Twenty-two passages of expository text were selected from daily newspaper articles. Each passage was edited and formatted to be 12 lines long, with up to 72 character positions per line when presented on the CRT. A set of three questions was prepared for each passage. These individual items included yes-no and true-false types of questions, mostly calling for retention of statements of fact in the passages. The purpose of the questions was to encourage subjects to focus their attention on reading the text for meaning, rather than attending to the display changes that occurred. The answers to the questions were neither scored nor analyzed.

## Experimental Manipulations

On selected fixations during reading (typically the fixations following the second and fifth forward saccades on a line), letters in certain regions of the display defined with respect to the reader's point of fixation[1] were replaced by other letters. This manipulation resulted in nonword letter strings in specific retinal regions. These are referred to as *regions of replaced letters*. In these regions, each letter was replaced by its most visually dissimilar letter from the same set, where letters were grouped into three sets: ascenders, descenders, and those letters that neither ascend above the others nor descend below the line. Visual similarity was determined from norms collected earlier with this display scope (Zola & Wolverton, 1983). Thus, replacement letters were as different from the original letters as possible yet within the limitations of the set of English letters, without changing the external shapes of the words.

In this study, there were two letter replacement conditions. In the *left condition*, all letters to the left of the point of fixation were replaced by other letters; in the *right condition*, all letters more than four to the right were replaced. In addition there was a control condition in which no letters were replaced. The replacement produced a letter string in the region of replaced letters that typically contained no English words and typically violated rules of English orthography but that did preserve many visual characteristics of the original text, such as external word shapes, word lengths, and punctuation. Examples of the appearance of a line of text under each of these conditions are shown in Figure 2.

Insert Figure 2 about here

The actual letter replacement occurred for one of two time periods. In the immediate condition the replacement was implemented at the beginning of the fixation and then the original letters from the text returned 100 ms later or at the onset of the next saccade, whichever came first. Thus, the erroneous letters were present for only the first 100 ms of a fixation in this condition. Replacement occurred very early in the fixation, that is, as soon as the saccadic movement was completed as indicated by no further movement of the eyes within a 4-ms period. With transmission lags in the equipment and in the fixation detection algorithm, the actual replacement was completed within the first 10 ms of the fixation.

In the delayed condition, the replacement occurred 100 ms after the beginning of the fixation and remained on the screen until the onset of the next saccadic movement. Thus, in this condition the errors were present only during the latter part of the fixation.

Combining the region and time of replacement factorially produced four experimental conditions: left-immediate, left-delayed, right-immediate and right-delayed. In addition there was a control condition in which display changes were produced in a similar manner 100 ms after the beginning of certain fixations, but in this case the text was simply replaced by itself, thus producing no detectable change in the display.

No changes were implemented for the right condition if the position of the eyes was determined to be more than 65 character positions to the right of the beginning of the line. Some lines were short enough that no letters would lie in the replacement region on such fixations, and hence the manipulation would have no effect. Because the control condition used the same algorithm as the right condition, this same restriction applied to it. A similar constraint was not necessary for the left condition since the replacement always followed a forward saccade and involved all letters to the left of the point of fixation.

Under certain circumstances a planned experimental manipulation was declared invalid and cancelled. When this occurred, that manipulation was rescheduled for the fixation after two additional forward saccades. For example, it was required that the replaced letters be present for at least 50 ms. If, in a delayed condition, the fixation was too short to meet this criterion, the replacement was implemented later. The same was true if a blink occurred during a critical fixation. If the first critical fixation on a line was rescheduled, then the second was also delayed until after the third forward saccade following that fixation. Thus, the fixations on which letter replacement occurred, or which were selected for the control condition, were always separated by at least two forward saccades.

Occasionally short saccades, made following the initial display change, were of small enough magnitude (about 1/2 character position or less) that the computer was unable to determine reliably, on-line, that a saccade was in fact in progress. In these cases, in the delayed conditions the line of text was not changed back to normal until the next saccade. Such fixations were marked in the data and excluded from analysis. Also, blinks and other eyelid movements occasionally resulted in the stimulation of a text change during a fixation. Fixations of this sort were also eliminated from the analysis. Thus, the only fixations included in the data analysis were those on which the display changed occurred at the appropriate times, according to the above description.

No replacement occurred on the first two lines of each passage. On the remaining 10 lines, the fixations following the second and fifth forward saccadic movements on the line were designated as critical fixations, that is, those on which the replacement was to occur. Thus, there were 20 critical fixations scheduled per passage. The five conditions were randomly assigned to each set of five consecutive critical fixations, so that each condition could occur four times per passage.

## Procedure

Because all subjects had participated in other eye movement research, they were already acquainted with laboratory procedures. Each subject was comfortably seated, and a bite bar, a forehead rest, and the eye tracking sensors were all appropriately adjusted. The subject then read a warm-up passage to become acquainted with this particular experimental task. During this passage, display changes occurred of the types used in the experiment, and similar comprehension questions were given following reading.

Prior to reading each passage, subjects were engaged in a calibration task, in which they looked directly at each of five dots that appeared, one at a time, equidistant across the CRT on the line where the text would later appear. As each dot was fixated, the subject pressed a button, which caused the computer to sample the eye movement monitor's voltage level corresponding to the eye's being directed at that location. This task was then repeated, and the computer checked for any instance in which the pairs of values obtained from corresponding points deviated an amount more than that equivalent to one letter position's eye movement. The dot then reappeared at those locations (if there were any) and further values were taken until two successive values were obtained that met the required criterion. The average of these two values was stored in a calibration table and used in a linear interpolation algorithm to identify eye position in the text as the subject was reading (McConkie, 1981).

After the calibration procedure was completed, pressing the button a final time caused the first line of text to appear. After reading each line, the subject pressed the button that brought the next line of text onto the CRT in less than 0.1 s. Following the final line of the passage, a dot appeared on the screen and the subject was engaged once again in the calibration task. The calibration values obtained prior to and following reading the passage were compared in order to determine whether the data were sufficiently reliable to include in the analysis (that is, whether they differed by less than an amount equivalent to an eye movement of 1.5 character positions), and their average was used as the calibration values in the final data reduction process.

After the second calibration task was completed, the first question appeared on the screen. Subjects responded by pressing the left button to indicate true or yes or the right buttom for false or no. By pressing the right button again after responding to the question, the next question was called onto the screen. After all three questions were answered, the calibration task was initiated for the next passage. This procedure was continued until 10 passages were read or until the subject requested a rest. During a second experimental session the subject read another warm-up passage and then the final 10 experimental passages. Each session required about one hour.

## Data Processing

As the data were being collected, an on-line algorithm identified the beginning and end of each saccadic movement and set unique bits in the data words to indicate each of these events. It also set a bit to indicate when a display change was initiated. This information was examined visually to ensure that the display changes were occurring appropriately, as described earlier. However, following the data collection the raw data were reanalyzed to identify the beginnings and ends of fixations more precisely. This program identified a saccadic movement on the basis of a velocity threshold that was low enough to detect movements of one letter position or less. It then proceeded through the data backwards in time to find the beginning of the saccade (i.e., the point at which no movement in the direction of the saccade occurred in a 4-ms period; the end of that period was identified as the end of the prior fixation) and then proceeded forward in time to find the end of the saccade, using the same threshold but selecting the beginning of the period as the beginning of the next fixation. It also identified disturbances in the eye movement pattern, which were not saccadic movements (i.e., blinks and squints), and marked the data so that they might be excluded from data analysis. In this process, the program created a second file, the "stack file," which contained a matrix with one row of entries for each saccade-fixation pair. Each row included information about the location of the fixation in the text, the duration of the fixation, the direction, length, duration, and velocity of each saccade, and indications of when disturbances occurred, when saccades occurred that were missed by the on-line algorithm, and when display changes occurred. The actual data analyses then proceeded using values selected from stack files.

## Results

With 14 subjects, each having the opportunity to be presented with 80 instances of each condition, a total of 1,120 critical fixations was planned for each condition. However, some planned manipulations never occurred because there were too few forward saccades on a line. Others were excluded from analysis because of blinks, data inaccuracy, or other problems in the data collection process. The number of actual data values used in any analysis depended on the number of good data points available on that dependent variable, but typically ranged from 8[illegible]0 to 1,000 per condition.

Eight dependent variables were used in the study: the duration of the fixation on which the display changed (Fixation F0) and of the fixation immediately following it the frequency of regressing on the saccade following F0 (saccade S1) and on the saccade following F1 (saccade S2), and the lengths of saccades S1 and S2, considering forward and regressive saccades separately. Because the distributions of fixation durations and of saccade lengths tend to be positively skewed, these data were first subjected to a log transformation. They were then subjected to an overall one-way analysis of variance with repeated measures to compare the means for the five conditions included in the study. Next *t* tests were performed to test the significance of four orthogonal contrasts: immediate versus delayed conditions, left versus right conditions, the interaction between these two sets of conditions, and all experimental conditions versus the control condition. Results of these tests, plus antilogs of the means, are presented in Table 1. Differences in the frequencies of regressing in the different conditions were tested with a chi-square test, with the significant effect also reported in Table 1. Significant effects were found for all dependent variables except the frequency and length of regressive saccades on saccade S2. The pattern of the effects was different for individual variables, however.

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Insert Table 1 about here

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The pattern obtained can best be described as follows. Erroneous letters to the left of the directly fixated letter increased the average duration of the F0 fixation, with this effect being greater when the errors were present early in the fixation rather than later. Erroneous letters also increased the frequency of regressions on the following saccade and shortened the lengths of those regressions. Erroneous letters to the right had very little effect on the average duration of the fixation on which they occurred, while reducing the frequency of regressions on the following saccade but with little effect on their lengths. All experimental conditions shortened the average length of S1 forward saccades, with this effect being greatest when the errors were present early rather than later in the fixation. This pattern was just reversed on the S2 saccade, with the average saccade length being affected only when the errors had been present during the latter part of the fixation. Finally, the average duration of the F1 fixation, the one following the presence of the errors, was increased when the errors had been to the right of the directly fixated letter, but not when they had been to the left.

This pattern provides evidence for the following assertions. First, the presence of errors during a fixation can affect both the duration of that fixation and the length and direction of the following saccade. However, the duration of the fixation is not affected if the errors lie a short distance to the right of the directly fixated letter. Second, the effects of the errors continue into the following fixation and saccade with the following pattern: Conditions having the greatest effect on fixation F0 (i.e., the _left_ conditions) have the least effect on fixation F1, and conditions having the greatest effect on saccade S1 (i.e., the _immediate_ conditions) have the least effect on saccade S2. Third, on saccade S1 there is a tendency for the eyes to be drawn toward the errors, thus increasing the frequency of regressions when the errors lay to the left, and decreasing their frequency when the errors lay to the right.

Testing the hypothesis that information to the left of the directly fixated letter is more critical early in the fixation, whereas that to the right is more critical in the latter part of the fixation, requires the ability to determine the degree of disruption produced by having errors present in a certain part of the retinal field at a particular time during a fixation. This determination is complicated by the nature of the effects that the different conditions had on the frequency distributions of the various dependent variables. The examination of these effects, however, is very revealing concerning temporal characteristics of processing during reading.

Effects of the Experimental Manipulations on Frequency Distributions

F0 fixation duration. Figure 3 presents the frequency distributions of the F0 fixation durations from three conditions: the control condition and the two immediate conditions. It is apparent that all three curves are very similar at the short fixation duration range but that they separate at the higher ranges. Figure 4 presents the cumulative frequency curves for the F0 fixation duration for all five conditions of the experiment, permitting a more accurate assessment of where in the distribution the curves separate. Kolmogorov-Smirnov tests indicate that the distributions of each of the experimental conditions deviate significantly from the control condition: left-immediate, $D = 0.2915$, $p < .001$; left-delayed, $D = 0.1479$, $p < .001$; right-immediate, $D = 0.0649$, $p < .05$; right-delayed, $D = 0.0840$, $p < .01$. Chi-square comparisons showed all experimental condition distributions to be significantly different from the control at the .001 level.

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Insert Figures 3 and 4 about here

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The data presented in Figures 3 and 4 can be used to answer several questions about the temporal characteristics of the processing taking place during a fixation. First, how long does it take for a change in the stimulus pattern, made during a fixation, to influence when the fixation will end? An examination of the curve for the left-delay condition in Figure 4 indicates that it separates from the control in the interval 181-200 ms. In this condition, the text was normal for the first 100 ms of the fixation. At that point, erroneous letters appeared to the left of the directly fixated letter. However, neither the fact of the change nor the existence of the errors seemed to have produced any effect on fixations that terminated during the next 80 ms. However, some fixations that were scheduled to end between 80 and 100 ms after the change (i.e., in the interval whose upper bound is 200 ms in Figure 4) were lengthened, reducing the number of fixations ending during that period. Thus, the time that it takes for stimulus manipulations of the type used here to reach the cortex and to affect the actual eye movement is less than 100 ms.

Although Figure 4 indicates that the curves for the right-immediate, right-delayed, and left-delayed conditions differ somewhat, all three appear to begin their deviation from the control condition in about the same time interval. Thus, if there is any difference in the speed with which the visual system responds to stimulus changes taking place in the left part of the fovea and those to the right but beyond the fovea, then this difference is small.

The fact that the curves for the right-immediate and right-delayed condition are so similar indicates that the presence of errors during the earlier versus the later part of the fixation had no effect on the duration of that fixation. Apparently, only the flicker associated with the changing of the letters midway through the fixation had an effect.

The left-immediate condition showed a pattern quite different from the other conditions. Erroneous letters in the left visual field early in the fixation increased the duration of the fixation on which the errors were present. Figure 4 indicates that the curve for this condition deviates from the control condition during the 141-160 ms interval and perhaps in the interval before that. Thus, some fixations that would normally have been 141-160 ms were still long enough to be influenced by the presence of erroneous letters to the left of the fixated letter.

This effect found in the left-immediate condition could be arising from any of three influences. First, subjects may have perceived the actual display change, even though it took place very early in the fixation. This seems unlikely to be the source of the effect because a similar display change occurred at the same time during the fixation in the right-immediate condition, but no similar effect was observed in that condition. Also, the effect observed in the left-immediate condition occurred substantially slower than those in other conditions that were known to be produced by the perception of stimulus change. Second, the subjects may have been reacting to the fact that the visual pattern of the stimulus was different on fixation F0 than it had been on the prior fixation. Earlier research makes this alternative unlikely, however. McConkie & Zola (1979, see also Rayner, McConkie, & Zola, 1980) found that when subjects read text printed in alternating case, if the case of every letter is changed during a saccade, causing a change in the shape of every letter and, consequently, of every word, this has no effect on the eye movements of the reader and is not reported as having been seen. Thus, a rather severe mismatch in the visual stimulus from one fixation to the next, at least as great as that in the present study, does not appear to produce the kind of effect observed in the left-immediate condition. The third alternative, the one that appears to be most plausible, is that the effect was due to processing problems which resulted from the orthographically inappropriate string of letters encountered on fixation F0. If that is the source of the effect, then the present data indicate that the orthographic characteristics of the text stimulus are coming into play within at least 140-160 ms following the onset of the fixation.[2] What is not known, of course, is whether the disruption resulted from a consideration of the orthographic characteristics of the stimulus pattern, an attempt to use the orthographic structure for phonetic recoding, or an attempt to use the letter pattern for lexical access or word identification.

The characteristics of these distributions make clear that it is difficult to determine whether one condition has a greater effect than another on the processing taking place. The size of the effect that an experimental manipulation has on some mean eye movement parameter, such as the fixation duration or saccade length, depends both on the frequency with which an effect occurred and the size of the effect when it occurred. Thus, although mean fixation duration or mean saccade length can be used to test whether an effect occurred, much care must be exercised in trying to conclude from such means that one condition had a greater effect than another. This, of course, makes it difficult to determine from the present data whether errors occurring earlier or later in the fixation or the ones at different retinal locations had more disruptive effects on reading.

S1 saccade direction and length. The next analysis investigated whether the direction and lengths of saccades were influenced by the experimental manipulations only if the F0 fixations were of a certain critical time duration. That is, it was hypothesized that a fixation had to be of at least a certain duration in order to provide the time necessary for the experimental manipulations used in this study to affect the direction and/or length of the following saccade. Figure 5 presents the proportion of S1 saccades that were regressive following F0 fixations of different durations, for three of the five conditions used in the study. Sample sizes underlying these proportions are much smaller than for those in the previous figures, so data are not presented for F0 fixation durations less than 120 ms and the data are grouped more coarsely at the upper end of the distribution. Also, the curves in the figure have been smoothed, with each point being an average of the value for that point with half the value for each adjacent point in the original data.

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Insert Figure 5 about here

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Figure 5 clearly indicates that the likelihood of making a regressive saccade is related to the duration of the preceding fixation and that this relationship is different for the different experimental conditions. In the left-immediate condition, regressions are more frequent than in the control at all F0 fixation durations, but primarily after 200 ms and peaking at the 300 ms interval. In fact, the unsmoothed data show a sharp peak at that point, with 43% of all saccades being regressive; intervals above and below show regressions 20% to 22% of the time. The left-delayed condition, on the other hand, does not show an increase in the frequency of regressions until the 301-350 ms interval. Apparently regressive eye movements can be induced within 201-250 ms following a stimulus change to the left of the directly fixated letter. At all intervals above that, the frequency of regressive saccades is greatly increased over the control condition.

A similar analysis was carried out for S1 forward saccade lengths by plotting the average length of all forward saccades that occurred following F0 fixations of different durations. No figure is presented because the curves for the different conditions were quite similar, with the only sizable and consistent difference being found with the right-immediate condition, which lay below the control group from the 221-240 ms interval through the 401-500 ms interval.

Figure 6 presents data on the lengths of regressive S1 saccades following F0 fixations of different durations. Larger intervals are used because of the smaller numbers of regressions, and the curves have not been smoothed. The data indicate that the presence of errors to the left of the directly-fixated letter early in the fixation (i.e., condition left-immediate) shortens the average lengths of regressions at least by the 161-220 ms interval. Having errors present only during the latter part of the fixation seems to have no effect until after 300 ms, or more than 200 ms after the errors appear.

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Insert Figure 6 about here

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The other dependent variables (i.e., durations of F1 fixations and lengths of S2 forward saccades) showed no such relations with the duration of the F0 fixations preceding them.

## DISCUSSION

### Response Time of the Eyes

Results of this study have yielded new information about the response time of the eyes both to stimulus change and to stimulus characteristics of a stable text pattern. The eyes can respond to a change in the stimulus pattern within less than 100 ms. Saccades that would normally occur sooner than that are not affected by the stimulus change; saccades that would occur later can be delayed. Furthermore, this time estimate is quite similar to the transmission time estimates mentioned earlier: 60 ms for neural activity from the retina to reach the visual cortex, and 30 ms for neural activity in the cortex to initiate an eye movement (Russo, 1978). Apparently there is very little processing time involved in deciding to postpone a saccade because of the occurrence of a stimulus change.

This finding allows us to add another temporal landmark to Figure 1. A point about 80-100 ms prior to the end of the fixation is labeled as the _visual stimulus influence deadline_. Any stimulus manipulations occurring after that point are too late to affect the temporal decision determining when the eyes are to be moved and probably too late to affect the spatial decision determining where to send the eyes next.

This estimate of the response time of the eyes is lower than those obtained by previous investigations, which typically indicated that even when the direction of the saccade and its target are known in advance, the response time is at least about 175 ms. Our estimate is similar to recent estimates of the time within which a change in a target stimulus location can have an influence on the length of a saccade to be made to that target. When the target is moved closer to the fixation point, a shortening of the saccade length is seen only if the saccade begins more than 80 ms following that movement, thus indicating the effect of stimulus factors on eye movements in just over 80 ms (Becker & Jurgens, 1979). We assume that these reduced estimates of saccadic response times result from there being less processing required to delay the onset or shorten the length of a saccade than to initiate a saccade. These estimates of saccadic response times indicate that if the minimum normal time required to initiate a saccade to a target is about 175 ms, then 80-100 ms of this time is involved in transmission (i.e., getting information to the saccadic control centers and from there to the eyes) with the remaining time, about 85 ms, required to program the saccade, even when its direction and extent are known in advance.

One implication of this finding is that time of initiation and length of a saccade can be influenced by mental processes occurring up to about 30 ms prior to the time that the saccade is to be made. This suggests a view of eye movement control during reading that is quite different from previous estimates based on saccadic eye movement reaction times. With those estimates, the final decision regarding the eye movement must be made from 175 to 200 ms prior to the initiation of a saccade (Rayner, 1983). These reaction time estimates require that the decision of when and where to move the eyes be made during the first 50 ms of average length fixations, providing very little time for the acquisition and processing of visual information available during that fixation. These estimates seemed to lend credence to arguments against immediate control of eye movements (Bouma & deVoogd, 1974; Shebilske, 1975) and support the notion that visual information must be acquired and used during only the initial part of the fixation. The present data indicate that the eyes can respond in a much shorter time than previously supposed and that the time available for processing information obtained during a fixation prior to the time the saccade decisions must be made is greater than previous estimates.

The results from this study also indicate the amount of time that elapses during a fixation before stimulus characteristics of the stable text pattern come into play in the processing. Within 140 to 160 ms after the onset of a fixation, the effects of orthographic irregularity become apparent in the eye movement data. By this time, not only letters have been perceived but also characteristics of the pattern of letters are influencing the processing. This is only 60 ms longer than the response time of the eyes. Thus, it appears that within 60 ms of the time that the neural activity stimulated by a new fixation begins to stimulate the cortex, the brain is responding to the letter sequence characteristics of the text. Fixations shorter than this are unaffected by the erroneous letters, though the next fixation may show effects. Of course, the actual processing may occur even sooner than this, with the results feeding back onto the eye movement control system only by this time; but we have no way of knowing this. Thus, from present information, another landmark can be added to the temporal processing chronology. This is entitled the _textual influence threshold_ because it is the earliest point at which we have evidence that an aspect of the stable text pattern (as opposed to stimulus changes) is being dealt with. This point is assumed to be 60 ms following the point at which the cortex is first stimulated by the pattern present on the fixation, or about 120 ms after the eyes stop for that fixation.

Eye Movement Patterns

Although the data provide information about how soon eye movement responses occur to certain stimulus manipulations, they also indicate that such responses are not always made. The most striking example of this is found in comparing the effects of the left and right conditions on the duration of fixation F0. Errors lying to the left inflate the fixation; errors to the right do not. The errors were perceived in the right conditions, as indicated by the fact that they had an effect on the direction and length of the following saccade. But they had no effect on the duration of the F0 fixation. This lack of effect is contrary to the common assumption that a fixation's duration is an indication of processing time required by the text perceived on that fixation. The presence of errors in the attended region must have induced processing difficulties; however, these difficulties were not reflected in the F0 fixation durations in the right conditions

There are three explanations for this difference between the right and left conditions. One possibility is that errors in the left part of the visual field are encountered earlier in the fixation than are errors to the right. In the present study, this could be either because of a left-to-right consideration of the text (Geyer, 1966; Gough, 1972) or because the transmission of more peripheral information is slower than that for more central information (Bouma, 1978). The errors in the right condition were more peripherally located than those in the left condition. Two attempts were made to find evidence for a left-to-right progression during a fixation. First, if there were such a progression, we would expect particularly long fixations to be long enough to show effects of errors in the right visual field. We examined the data from an earlier study in which erroneous letters had been present more than three or five letters to the right of the directly fixated letter (McConkie, Underwood, Wolverton, & Zola, 1983) in order to determine whether these errors selectively produced longer F0 fixation durations in the upper part of the frequency distribution. No such effect could be found. The frequency distributions for control and right conditions in that study were very similar throughout the entire range. Second, we expected that if there were a left-to-right progression, having errors in the left visual field early in the fixation (i.e., left-immediate condition) would produce greater disruption of reading than having them later (i.e., left-delayed condition), whereas this trend would be reversed in the right visual field. Here, the right-delayed condition should show more disruption than the right-immediate condition. This comparison was complicated by the fact that the effect of the experimental manipulations was to distort the frequency distributions in characteristic ways, making it inappropriate to simply compare mean fixation durations and saccade lengths. Thus, although the mean F0 fixation duration was greater in the left-immediate than in the left-delayed condition, this was probably at least partially due to the fact that the errors appeared in the delayed condition later in the fixation, too late, in many instances, for them to affect the duration of that fixation or the direction or length of the following saccade. However, the delayed condition showed a more severe shortening of saccade S2. Thus, errors present early in the fixation had greater immediate effects, whereas errors present later in the fixation produced greater effects later in the eye movement sequence. Because we presently have no way of accumulating the various ways that the eye movement pattern can be changed by the presence of errors into a single index of degree of disruption, we are not able to determine whether the left-immediate condition produced greater disruption than did the left-delayed. The same problem exists in trying to compare the right-immediate with the right-delayed conditions. Neither showed any effect on the F0 fixation duration. The immediate condition shortened the following saccade the most of any condition. Again, this appears to be the case because errors appearing only later in the fixation were too late to have immediate effects. Furthermore, the delayed condition showed a greater shortening of the length of the S2 saccade. The present data provide no evidence for a left-to-right progression in the acquisition or use of the text during a fixation, though a clean test of the hypothesis is not possible. Evidence from another study specifically designed to test this possibility, however, yielded negative results (Blanchard, McConkie, Zola, & Wolverton, 1984). Thus, we strongly doubt that a left-to-right scan is the explanation for the difference in eye movement response between the _left_ and _right_ conditions.

There are two pieces of evidence against the transmission time differential hypothesis. The first was mentioned in the last paragraph. If the difference between left and right conditions were due to the errors located more peripherally in the right visual field having a slower transmission rate than those in the left fovea, we would expect the frequency distribution of F0 fixation duration to be distorted in the same manner in the two conditions, but with the distortion simply beginning later in the distribution in the *right* condition. However, in data from our earlier study that did not have display changes occurring during fixations, the distribution for the *right* conditions was very similar to that for the control condition throughout the distribution. The second piece of evidence has to do with when the effect of the stimulus change was seen on the eye movement pattern in the left- and right-delayed conditions. An examination of the F0 fixation duration frequency distribution indicates that the effect showed up just as early *right* condition as in the *left*, with no evidence for a substantial transmission delay in the *right* condition. Thus, there was no evidence that transmission of this stimulus change was much slower for letters to the right of the fovea than it was for letters directly in and to the left of the fovea. If there is a transmission difference, it is not of the magnitude necessary to account for the lack of an effect of the *right* conditions on the F0 fixation duration.

The third possible explanation for the difference between the *left* and *right* conditions has to do with the nature of the eye movement elicited by the erroneous letters in the respective conditions. Errors to the left tend to induce regressive movements. Furthermore, it is only when regressions are made that the F0 fixation duration is increased in the *left* condition, with this increase averaging approximately 150 ms. When the following saccade is forward, the F0 fixation durations are not different from those of the control condition when selected in a similar manner (McConkie et al., 1983). Thus it appears that when a regression is stimulated on saccade S1, it results not only in the cancellation of a forward saccade but also in the addition of a considerable amount of time necessary for programming the regression. This reprogramming results in the inflated F0 fixation durations.

The data on the directions and lengths of saccades following fixations of different durations provides additional evidence that the making of regressions on saccade S1 in response to errors to the left required additional processing time. In the left-immediate condition an increase in the frequency of regressions appeared only when F0 fixations were more than about 200 ms in duration. Similarly, in the left-delayed condition, increases in regressions were found only when the F0 fixations were more than about 300 ms. It appears that the programming of a regression in response to information first seen on that fixation requires added processing time, resulting in F0 fixations increasing by about 100 ms.

In other cases when errors are present to the left of the directly fixated letter, a forward movement is made on the S1 saccade followed by a regression on the next saccade. In this case, the fixation immediately prior to the regression (i.e., fixation F1) was not longer than normal (McConkie et al., 1983). Thus, when a regression is made in response to information obtained on an earlier fixation, an extra long fixation is not required. Presumably, any additional processing time required to program the regressive eye movement occurred during the natural period of the fixations involved. Because the durations of fixations preceding regressions tend to be shorter than average in normal reading, this raises the possibility that in most instances regressions are made, not in response to information gained on the immediately preceding fixation, but in response to information gained earlier.

Apparently, the cancellation of regressions that would normally have occurred does not require the same additional reprogramming time. The right conditions resulted in a reduction in the number of regressions, but with no accompanying increase in the average FO fixation duration. This is an unexpected result because, like the inducing of a regression, this involves changing the direction of the following saccade, an event that is typically found to require additional processing time (Becker & Jurgens, 1979).

## The Determination of Fixation Durations

The results just described indicate that several factors are involved in determining how long the eyes remain in a fixation during reading. First, there are factors operating prior to the fixation itself, quite independent of what is seen during that fixation. These factors can affect the fixation duration in two ways. They can prevent the fixation from lasting long enough to be influenced by text seen on that fixation. Only if a fixation continues for a certain period of time is it possible for a given aspect of the text to influence the duration of that fixation. What the length of this period is for different aspects of the text is a matter that requires further investigation. In addition, the duration of one fixation can be increased as a result of the processing of information acquired on the previous fixation. This will be referred to as lagged processing effects. A clear example of such effects in the present study is the inflation of fix ion F1 as a result of encountering errors on the previous fixation. Second, there are eye movement factors that come into play. If the presently viewed visual pattern calls for a regression on the following saccade, the fixation is increased in duration. No similar added time seems to be required if a regression is to be canceled or if a forward saccade is to be shortened. This suggests that the normal case for skilled readers is to cast their eyes rightward along the line and that moving leftward is a special case that requires added time. However, when a stimulus pattern on fixation F0 fails to induce a regression on the following saccade, but only on the saccade following that (i.e., S2), neither fixation F0 or F1 is affected. The required extra time seems to be available during the two fixations, without requiring extra fixation time. Third, there may be an influence related to where in the visual field a certain word lies. In the present study, errors increased the F0 fixation duration only if they lay to the left of the directly fixated letter. Whether retinal location of an item influences fixation duration only when it has an effect on the pattern of eye movements induced must be a matter for further investigation. Fourth, there is an influence resulting from characteristics of the text seen during that fixation. Characteristics that produce processing difficulty can, but do not always, increase the duration of the fixation.

Together, these results indicate that the time the eyes remain in a fixation is not a simple indication of the time required to process the information seen during that fixation. The duration of a fixation in reading is complexly determined, and the nature of the determining factors must be explored in detail if we are to use eye movement data to accurately indicate the temporal characteristics of language processing.

There is one puzzling characteristic of the data of this study, as well as that of an earlier study (McConkie et al., 1983). Whereas several studies have reported relationships between characteristics of words fixated and the durations of those fixations during reading (Kliegl, Olson, & Davidson, 1983; Rayner, 1977; Zola, 1981), our studies have found no such effects in most conditions. Replacing all letters more than three, four, or five to the right of the directly fixated letter had no effect on the duration of the fixation other than that produced by changing the text during the fixation. Errors to the left of the fixated letter had an effect only if a regression was made. This raises the question of why errors have so little effect in the present study when the effects of word characteristics seem so well documented.

One possibility is that the effects commonly seen in normal reading data are often the result of obtaining visual information peripherally. Thus, when a word is fixated, sufficient prior information has been gained about it on previous fixations that the remaining processing can take place early enough that its characteristics can affect that fixation. Whether peripherally obtained visual information could be extracted or acquired and used in such a way during reading is presently a matter of dispute (McClelland & O'Regan, 1981; Paap & Newsome, 1981; Rayner, McConkie, & Ehrlich, 1978), but our own recent studies lead us to doubt this explanation (McConkie, Zola, Blanchard, & Wolverton, 1982). A second possibility is that word variables can affect the eye movement system earlier than can letter sequence irregularities because the processing proceeds more rapidly and smoothly with normal words. Encountering erroneous letters of the type used here must interfere with the normal flow of processing, and the system may then have to invoke error-correction procedures, all of which takes time. The effects of this added processing may not feed back into the eye movement control system as rapidly as information from normal language processing does. This hypothesis requires further study.

Summary

This article has described a framework for considering the chronology of processing events associated with a fixation during reading. It has demonstrated that the response time of the eyes is shorter than has usually been proposed in theories of visual processing in reading. Thus, eye movement decisions are made later in the fixation than has often been assumed, allowing more time prior to those decisions for the processing of stimuli perceived on that fixation. At the same time, we have emphasized that much of the processing takes place too late to affect the immediately following saccade and hence is revealed only later in the eye movement pattern. This study provided examples of such delayed effects. Finally, the article introduced a methodology by which it is possible to investigate the amount of time required for different aspects of the text stimulus available during a fixation in reading to affect the ongoing processing taking place as reflected in changes in eye movement characteristics.

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Rod Underwood's present address is Claremont Teachers College, Claremont, Western Australia, 6010.

Copies of this paper can be obtained by writing to George W. McConkie, Center for the Study of Reading, 51 Gerty Drive, Champaign, IL 61820.

## Footnotes

[1]We will speak of the letter position on which the eyes are centered, according to the eye position data, as being the point of fixation or the directly-fixated letter. This is not meant to suggest that this particular letter is specifically attended, or that the reader is necessarily looking at that letter more than others nearby. It is simply a convenient way of describing the rotational position of the eyes during a fixation in reading. It indicates that this position is approximately the same as it would be if the subject were asked to look directly at that letter position.

[2]We have recently completed another study for a somewhat different purpose, but which involved reading text in which occasional words had been replaced by strings of letters that violated English orthographic regularities. This study involved no eye movement contingent display changes. Fixations were identified which were centered on these non-orthographic strings, and were preceded by fixations lying at least six character positions to the left of the string. Similar fixations were identified which were centered on unreplaced words. Frequency distributions for fixation durations in these two cases showed the same pattern as in the present study: they were similar at the lower durations and separated in the 140-159 ms interval. This provides added evidence that the data pattern in the present study was the result of responding to orthographic irregularity and not to display changes or to mismatches in the visual pattern between successive fixations.

## Figure Captions

Figure 1. Perceptual events associated with a fixation during reading. Time in ms is represented on the ordinate, and eye position on the abscissa. Peripheral events are indicated above the curve, and central events below the curve. The fixation represented is 220 ms in duration, and is followed by a 30 ms saccade.

Figure 2. Appearance of part of a line of text in Left and Right conditions on fixations on which erroneous letters were present. The directly fixated letter is indicated below the text.

Figure 3. Frequency distributions of F0 fixation durations for three conditions: Control, Left-Immediate and Right-Immediate.

Figure 4. Cumulative frequency curves for F0 fixation durations for all five conditions included in this experiment. The value on the horizontal axis indicates the upper bound of each interval.

Figure 5. Proportion of S1 saccades that are regressive as a function of the duration of the preceding fixation F0 for the control, Left-Immediate and Left-Delayed conditions.

Figure 6. Mean lengths of regressive S1 saccades after F0 fixations of different durations.

Table 1

Effects of the Experimental Manipulations on Eye Movement Characteristics

| | | Fixation Duration[1] | | Saccade Length[1] Forward | | Saccade Length[1] Regressive | Frequency of Regressive Saccades[2] |
|---|---|---|---|---|---|---|---|
| | | F0 | F1 | S1 | S2 | S1 | S1 |
| Control | | 202.4 | 207.2 | 7.70 | 7.16 | 5.11 | 13.5% |
| Left-Immediate | | 241.6 | 209.6 | 7.23 | 7.30 | 3.27 | 21.4% |
| Left-Delayed | | 225.0 | 211.9 | 7.44 | 6.84 | 4.23 | 18.4% |
| Right-Immediate | | 205.8 | 217.6 | 7.01 | 7.01 | 5.25 | 10.4% |
| Right-Delayed | | 211.8 | 216.5 | 7.23 | 6.83 | 4.95 | 8.4% |
| **Results of Significance Tests** | | | | | | | |
| Overall Test | F | 30.10 | 2.59 | 5.50 | 2.71 | 10.33 | $X^2$=89.90 |
| | df | 4,5000 | 4,3807 | 4,3961 | 4,3137 | 4,659 | 4 df |
| | p | .00 | .03 | .00 | .03 | .00 | P<.005 |
| Immediate vs. Delay | t | 1.63 | 0.22 | 2.39 | 2.63 | 1.45 | |
| | p | .10 | .82 | .02 | .01 | .15 | |
| Left vs. Right | t | 8.40 | 2.22 | 1.59 | 1.22 | 4.55 | |
| | p | .00 | .03 | .11 | .22 | .00 | |
| Interaction | t | 3.80 | 0.57 | 0.50 | 1.15 | 2.29 | |
| | p | .00 | .57 | .62 | .25 | .02 | |
| Experimental vs. Control | t | 5.89 | 2.19 | 3.65 | 1.24 | 2.10 | |
| | p | .00 | .03 | .00 | .21 | .04 | |

1 Repeated measures analyses were conducted using log values. This table presents the anti-log equivalents to the Mean log values obtained.

2 N's on which these percentages are based range from 892 to 980

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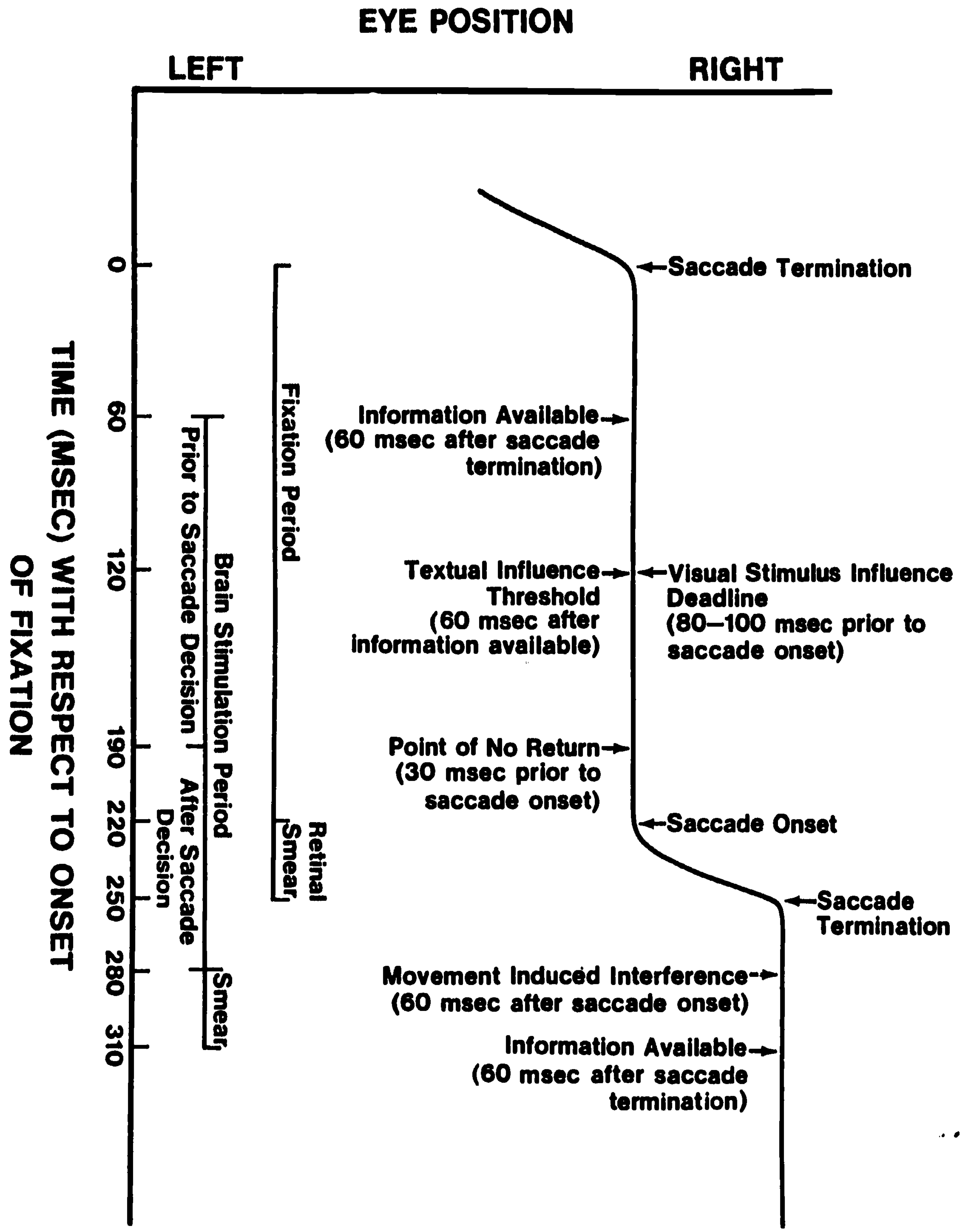
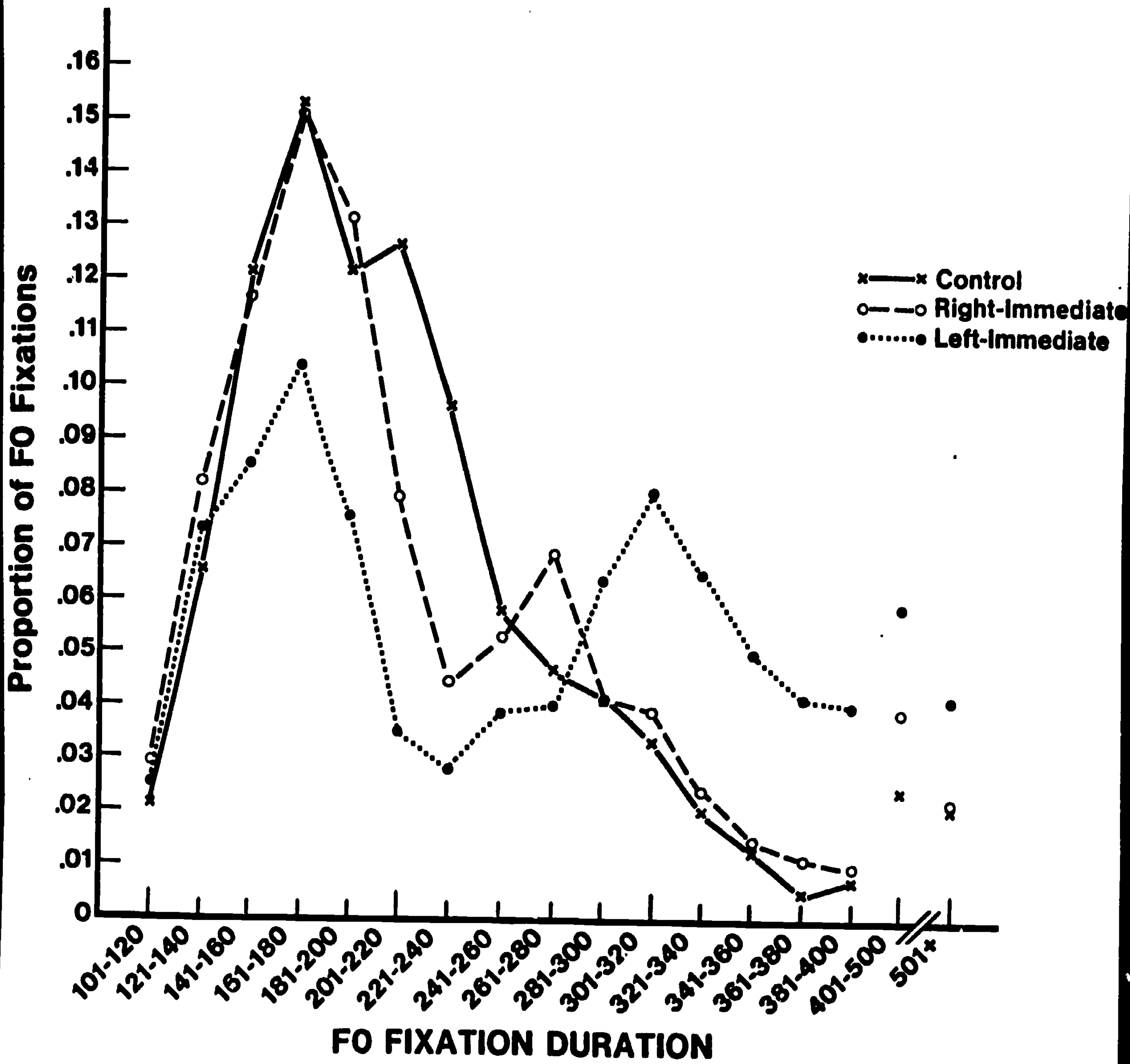
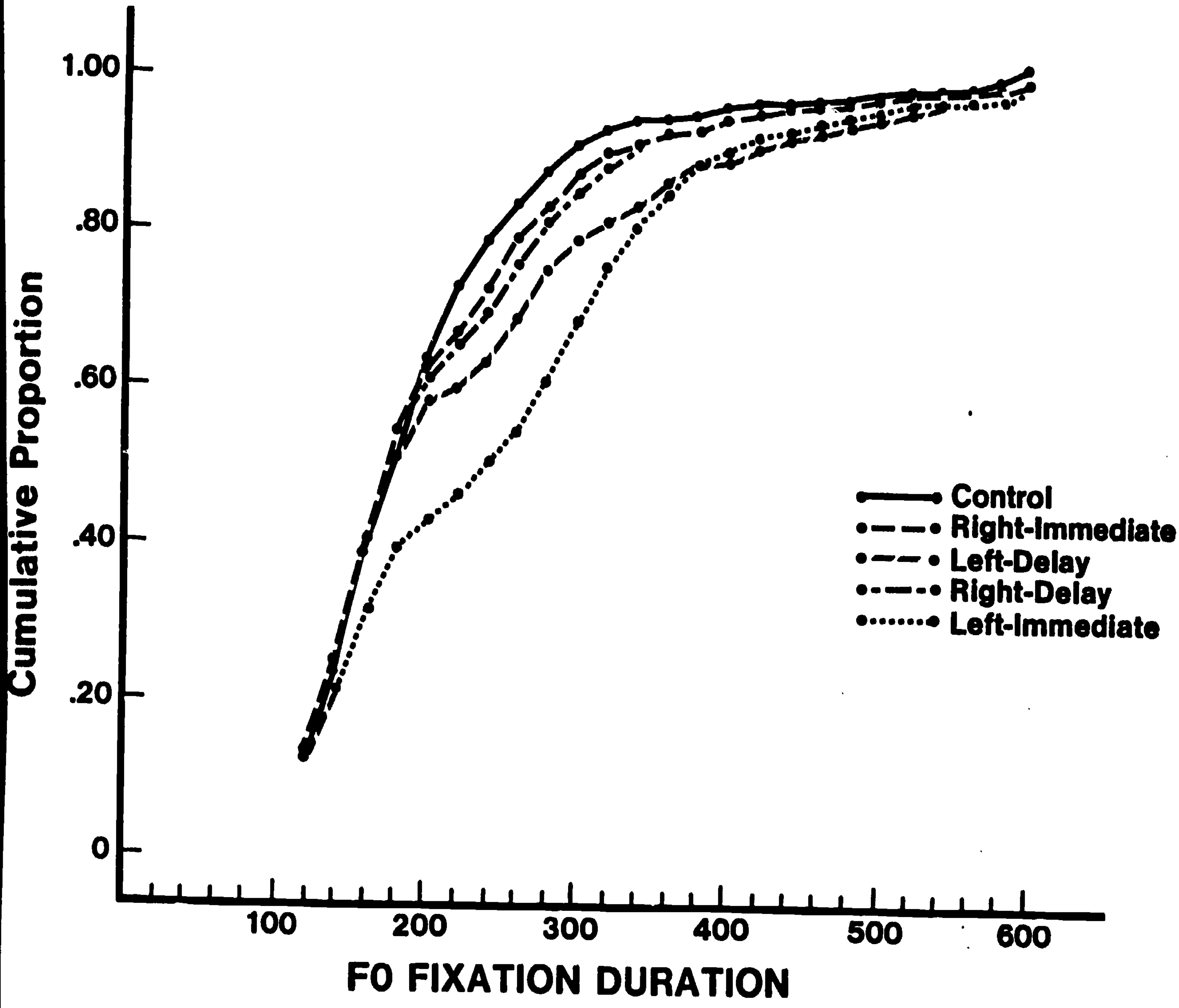

EYE POSITION
LEFT
RIGHT
TIME (MSEC) WITH RESPECT TO ONSET OF FIXATION
0
60
120
190
220
250
280
310
Prior to Saccade Decision
After Saccade Decision
Brain Stimulation Period
Smear
Fixation Period
Retinal Smear
Saccade Termination
Information Available (60 msec after saccade termination)
Textual Influence Threshold (60 msec after information available)
Visual Stimulus Influence Deadline (80–100 msec prior to saccade onset)
Point of No Return (30 msec prior to saccade onset)
Saccade Onset
Saccade Termination
Movement Induced Interference (60 msec after saccade onset)
Information Available (60 msec after saccade termination)

ORIGINAL LINE: The issuance of the stamp was the result of the

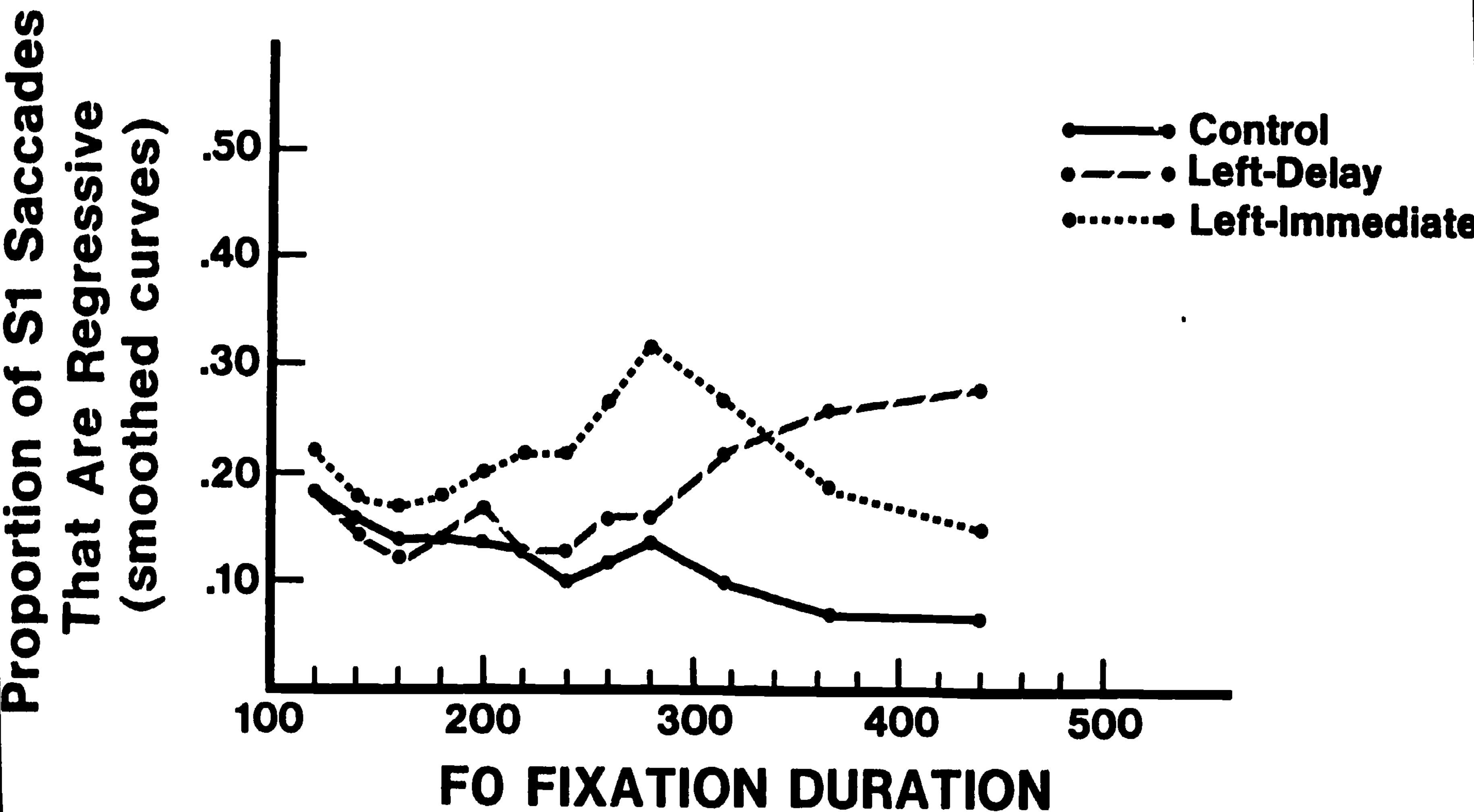
LEFT CONDITION: The issuanvn ui hfn rhmaj xmr hfn snrokb ui hfn

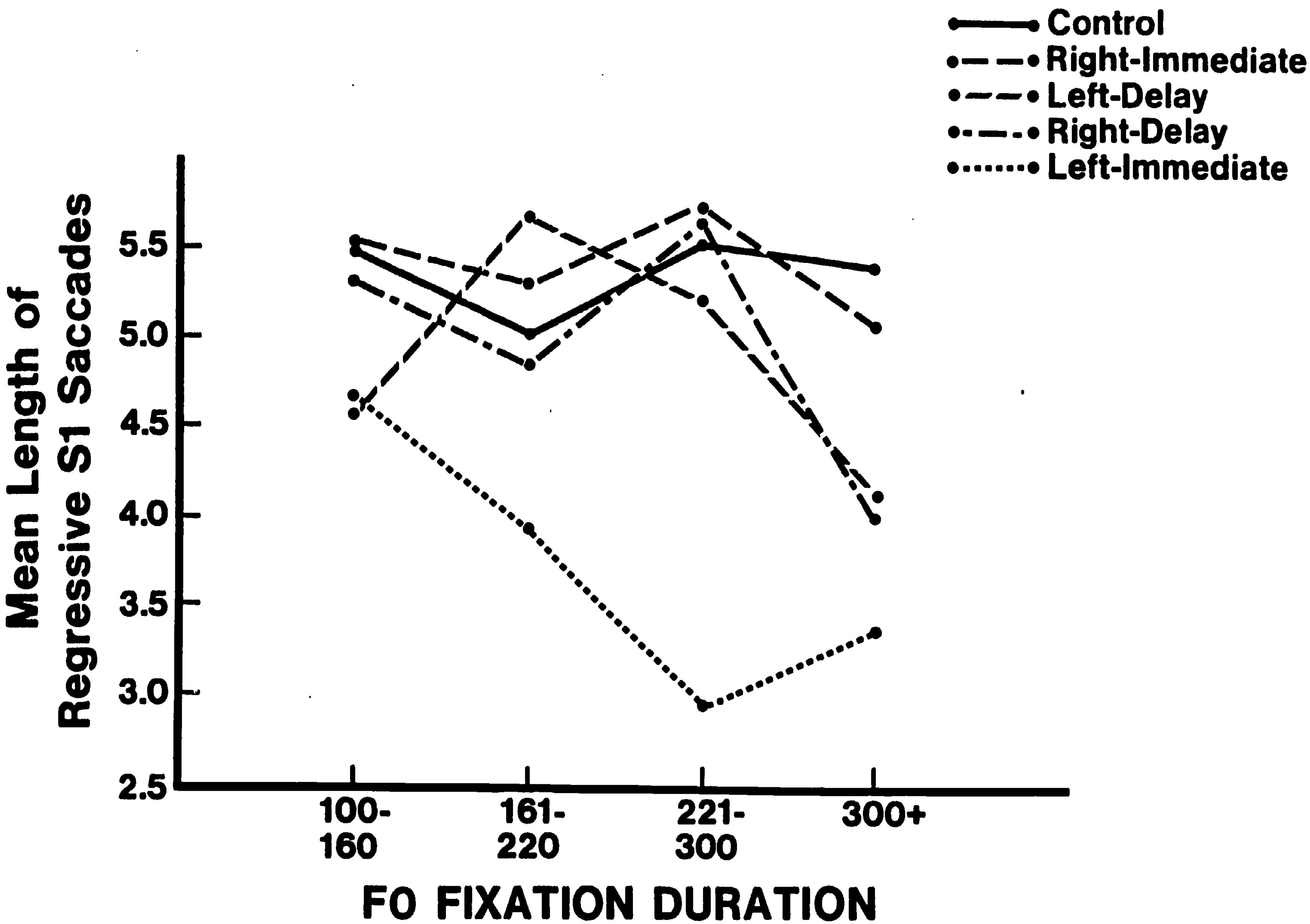
RIGHT CONDITION: Xfn brromevn ui hfn rhmaj xms the result of the


Proportion of F0 Fixations
.16
.15
.14
.13
.12
.11
.10
.09
.08
.07
.06
.05
.04
.03
.02
.01
0
Control
Right-Immediate
Left-Immediate
101-120
121-140
141-160
161-180
181-200
201-220
221-240
241-260
261-280
281-300
301-320
321-340
341-360
361-380
381-400
401-500
501+
F0 FIXATION DURATION



Cumulative Proportion
1.00
.80
.60
.40
.20
0
100
200
300
400
500
600
F0 FIXATION DURATION
Control
Right-Immediate
Left-Delay
Right-Delay
Left-Immediate


Proportion of S1 Saccades
That Are Regressive
(smoothed curves)
.50
.40
.30
.20
.10
100
200
300
400
500
F0 FIXATION DURATION
Control
Left-Delay
Left-Immediate


Control
Right-Immediate
Left-Delay
Right-Delay
Left-Immediate
Mean Length of
Regressive S1 Saccades
5.5
5.0
4.5
4.0
3.5
3.0
2.5
100-
160
161-
220
221-
300
300+
FO FIXATION DURATION

65