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ABSTRACT

A computer-based Eye-Movement Controlled Display System was developed for the study of perceptual processes in reading. Studies were conducted to identify the region from which skilled readers pick up various types of visual information during a fixation while reading. The results indicated that the subjects acquired word length pattern information at least 12 to 15 character positions to the right of the fixation point, and that this information primarily influenced saccade lengths. Specific letter and word shape information was acquired no further than 12 or 13 character positions to the right of the fixation point. It appeared that words were given a semantic interpretation only if they began no more than 5 or 6 character positions to the right of the fixation point. The perceptual span was found to be asymmetric, with the subjects acquiring information no further than 4 character positions to the left of the fixation point, and perhaps less. (Author/RB)

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IDENTIFYING THE SPAN OF THE EFFECTIVE STIMULUS IN READING

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PREFACE

The research described in this report was carried out at the Artificial Intelligence Laboratory at Massachusetts Institute of Technology between September, 1971, and August, 1972, with a short return trip in January, 1973. This was made possible by a Special Fellowship from the National Institute of Mental Health to the senior author, who was on sabbatic leave from Cornell University, and the present grant from the U.S. Office of Education which provided support for the junior author.

The Boundary Study described in this report served as the doctoral dissertation for the junior author. Much of the review of literature in Chapter 1 is taken from that document as well.

The authors wish to express their gratitude to Dr. Marvin Minsky and Dr. Russell Noftsker for the opportunity of spending this time at the Artificial Intelligence Laboratory and of having access to its extensive computing facilities. David Silver, a staff programmer there, did much of the programming involved and introduced the authors into the complexities of assembly-language programming. His contribution to this research was invaluable. The principal and staff at Cambridge High and Latin, a high school in Cambridge, Massachusetts, identified potential subjects for us, and put us in contact with them. This research also benefited from our conversations with Steven Reder, then a graduate student at Rockefeller University, who was engaged in much the same type of research at the same time. We are also greatly indebted to Dr. Richard Monty who first suggested the MIT Artificial Intelligence Laboratory as a possible place to carry out this research. Gary Wolverton, a graduate student at Cornell University, provided help with data analysis, and Sue Rayner did most of the key punching which was involved.

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CHAPTER 1

INTRODUCTION AND LITERATURE REVIEW

The experimental study of reading in psychology has a rich history dating back to Javal's observation that the eyes execute a series of saccadic movements as a person reads a line of print (Huey, 1908). Much of the basic knowledge that we have concerning skilled reading was discovered around the turn of the century and was reviewed by Huey (1908) and Woodworth (1938). Since that time, relatively little has been added to understanding the processes involved. Research on reading among psychologists began to dwindle in the 1920's. Undoubtedly, the difficulty of studying a process as rapid and as private as skilled reading, coupled with the rise of Behaviorism and the focus on observable behavior, led to this disinterest. Also, researchers in the field of reading began to separate from the main stream of psychology and to form their own professional organizations and journals in the 1920s (Blumenthal, 1970). Soon reading laboratories began to be centered in schools of education. Since education is mainly concerned with the improvement of learning, many people interested in reading directed their research to comparing the effectiveness of different methods of reading instruction. It was also during this time that much emphasis was placed on the development of reading tests and of materials and techniques which could be used to improve reading.

The net result of this shift from psychology to education, together with the rise of Behaviorism, was that the research on the basic cognitive processes underlying reading virtually ceased. Recently, there has been an upsurge of interest in this area once again, stimulated by the emergence of cognitive psychology and psycholinguistics. Despite renewed activity in basic reading research, it is still the case that few of these studies involve subjects in the highest form of skilled reading: rapid, silent reading. Of those studies which focus on skilled reading, the vast majority involve reading aloud, experimenter paced reading, or tasks quite unlike normal reading. From these types of studies, several theories have recently been proposed to account for skilled reading (Smith, 1971; Mackworth, 1972; Hochberg, 1970; Levin and Kaplan, 1970).

Within these theories, a number of old research questions have been revived once again. These include: (1) What is the size of the area from which the reader acquires visual information during a fixation? (2) What guides the reader's eyes as he reads? (3) What part do cues from peripheral vision play in reading? The research which will be described in later chapters was concerned with these interrelated questions. Some new techniques for investigating these questions will be described which involve computerized eye tracking and text display changes during reading.

The remainder of the present chapter will be devoted to a review of the research literature related to the three questions listed above.

The Perceptual Span in Reading

Determining the size of the area from which a person picks up information during a fixation in reading has long intrigued psychologists. If a reader fixates on a certain letter on a page of text, he finds that he can recognize words two or three lines above and below that being fixated. In addition, he can recognize words some distance to the left and right of his fixation. Beyond these areas punctuation marks, capital letters, word boundaries, and the beginnings and ends of paragraphs are visible (Woodworth, 1938). On the other hand, if a string of letters is presented visually for a few milliseconds, the reader is able to identify only 4 to 6 of the letters (Sperling, 1960). Somewhere between these two extremes must lie the size of the perceptual span in reading.

Four general types of research have been used to identify the perceputal span in reading. The first and simplest type of research has been to divide the number of letters per line by the number of fixations per line (Taylor, 1957; Taylor, 1965). Observations such as these have generally found that skilled readers make fewer fixations per line, suggesting that they have a wider perceptual span. However, Hochberg (1970) has argued that this difference in number of fixations is not the result of differences in what the readers can actually see, but it reflects differences in cognitive activities during each fixation. This method of estimating the perceptual span is also based on the assumption that on successive fixations the perceptual spans do not overlap or that they overlap the same amount. This assumption is likely false.

The second, and oldest, type of research has utilized the tachistoscopic presentation of letters and words. Since the material is generally presented for very brief exposures to exclude the possibility of an eye movement during the presentation this method has often been thought of as being analogous to a single fixation in reading. The earliest studies by Cattell and by Erdmann and Dodge (described by Huey, 1908 and Woodworth, 1938), found that the perceptual span for letters combined in words is much greater than for non-word strings. With an exposure of 10 milliseconds, it was found that a subject could read 3-4 unconnected letters, 2 unconnected short words, or 4 connected short words. Recent research (Wheeler, 1970; Reicher, 1969; Baron and Thurston, 1973) has found that it is easier to decide which of two letters was presented tachistoscopically if the critical letter was in a word rather than a non-word letter string or in isolation. Tulving and Gold (1963) and Morton (1964) have reported that increased contextual information increases the amount that can be reported from a tachistoscopic presentation. All of these recent studies have shown that the number of letters or words that can be reported depends on the redundancy of the stimulus.

A limitation of this method of determining the perceptual span was mentioned by Woodworth (1938) and later verified by Sperling (1960). Sperling found that subjects are able to see much more than they can retain and later report. Thus, what subjects report from a brief presentation cannot be taken as a complete specification of what they actually saw. Geyer (1970) has pointed out that even if the verbal report coincided with what the person actually saw, there is no particular reason to believe that the perceptual span obtained in a tachistoscopic presentation actually coincides with that of a fixation during reading. One conclusion that recent research in cognitive psychology is forcing upon us is that subjects are able to adapt their strategies to the task in which they are engaged. It is very likely that normal reading and tachistoscopic report vary enough to induce different strategies in readers. The tachistoscopic studies generally involve the isolated presentation of some stimulus material, whereas reading involves fixations at the rate of four per second, with a very complex stimulus pattern having a great deal of redundancy. Due to these differences, the perceptual span in reading could be either larger or smaller than that found with tachistoscopic presentations. It could be larger because the contextual constraint allows a reader to identify words with less visual information, or it could be smaller because of the rapid sequence of fixations and the complexity of the surrounding stimulus pattern which may lead to what Mackworth (1965) has referred to as tunnel vision.

The third method of investigating the perceptual span is to have a subject fixate some point and then have him identify stimuli presented at various distances from his fixation point (Huey, 1908; Woodworth, 1938; Feinberg, 1949; Bouma, 1973). Research of this type has generally found that only four or five letters around the fixation point are identified with near 100% accuracy and that from the point of clearest vision outward, in either direction, words and letters are seen with decreasing clarity. Although this information regarding the area of visual acuity is valuable for setting the upper bounds of the perceptual span, it cannot be taken as evidence for what information a person actually uses during a fixation in reading.

The fourth technique is to manipulate the amount of text which is visible to a subject at a given moment. Poulton (1962) had subjects read aloud from text over which a mask containing a window was passed. The speed and size of the window varied systematically on different trials, and the subjects' eye movements were recorded electronically. In this research, the text was immobile, and the window passed over it, allowing only a certain amount to be seen at once. Newman (1966), on the other hand, kept the window stable and passed the text beneath it. He presented text on a screen, with the letters moving from right to left, and varied the number of letters on the screen at any moment, the number of new letters that were added at once, and the rate at which they were added. Both investigators found that smaller windows create greater disruption in reading. These techniques, however, disrupt normal reading because the person's natural eye movements are disrupted.

None of these techniques appear to provide a very definite answer to the original question. The last three techniques involve tasks rather unlike normal, silent reading, and it is possible that the demands of these various tasks induce strategies in the subjects that are quite different from those normally used in reading. It may well be that the perceptual span varies with the task structure. The first technique is based on questionable assumptions. Thus, the differences in the estimates of the size of the perceptual span which have come from these studies is likely the result of different strategies on the part of the subjects, different amounts of context in the stimulus materials, etc.

The ideal situation for answering the perceptual span question would be one in which the subject is involved in the act of reading normal text to understand its meaning. Then a means would be used to obtain data from the subject concerning the perceptual span as he is engaged in this, the normal reading task. Once this is achieved, the answer to the question of how far into the periphery he acquires visual information is likely to be quite complex. First, we must recognize that it is likely that different aspects of the visual stimulus are probably acquired at different distances into the periphery. Thus, there is probably not a single perceptual span, but a number of perceptual spans for information of different types: full featural detail of letters may be obtained only a certain distance from central vision, with information about general external word shape, word length patterns, location of such irregularities as punctuation, italicization, etc., and location of ends of lines being obtained farther and farther into the periphery. The investigation must then explore how far into the periphery each of these, and other, types of visual information is obtained by the reader. Second, we must make a distinction between information registered by the visual system and information actually used in reading. It may be that during a fixation the visual information from a rather large area is actually registered at some level in the visual system, and thus could be used for some purpose, but that in the act of reading the person processes and uses the information from a much more restricted area. In the investigation of reading, we are most interested in defining this latter area; the region from which the reader obtains information which is actually used in the reading act. Finally, it must be recognized that the size of the regions from which different types of visual information are acquired and used in reading may vary from fixation to fixation. It is conceivable that the reading span may vary with such factors as syntactic structure of the sentence, amount of redundancy of the text, etc.

What Determines the Readers' Eye Movements?

During reading there are two important eye movement components called fixations and saccades. Fixations, which take up over 90% of the time, are periods when the eye is relatively still. It is during these periods when visual information is extracted from the text. The remaining 10% of the time is spent in saccades, where the eye moves from one position to another. Thus, there are two questions which must be asked about eye movement behavior. What determines how long the eye will remain in a fixation? And what determines where the eye will be sent in the next saccade?

Prior to discussing these questions, two characteristics of the saccadic movement need to be considered: visual input during the saccade, and the nature of the saccadic movement itself.

Although there is a great deal of controversy on the topic, it is generally believed that there is a period of visual suppression during a saccade. The controversy centers around which of two possible mechanisms, central inhibition or retinal blurring is responsible for the suppression. The first position, central inhibition, assumes that visual input is blanked out or suppressed to some degree by some central inhibitory process during this period. The retinal blur position also assumes that little or no useful visual information is acquired during the saccade, but that this is due to the optical blurring or smearing of the visual image across the retina as the eye moves at a high rate during the saccadic movement. The majority of the research (Volkman, 1962; Volkman, Schick and Riggs, 1968; Uttal and Smith, 1968) confirms the retinal blur position. That is, the evidence indicates that visual input is not totally suppressed during a saccadic movement. However, there is also evidence that visual sensitivity is reduced substantially, not only during the movement itself, but also shortly before and after the eye has settled on a new position (Haber and Hershenson, 1973). Thus, it appears that the lack of useful visual input during the saccade is not totally accounted for by the notion of retinal blur.

While little is known about the central inhibitory mechanism that causes the visual suppression found during and immediately after a saccade, Haber and Hershenson (1973) indicate that it is functional in that it minimizes the perception of blur which might occur during the saccadic movement. Volkman (1962) has shown that there is a rise in visual thresholds during movement. Although the change is not great considering the total range of sensitivity of the visual system, it is probably enough to reduce the blur below annoyance levels. This change in threshold is probably also enough to reduce the sensitivity of details that pass across the retina and the chances of noticing new information or fine detail during saccadic movement is thus greatly reduced (Haber and Hershenson, 1973).

Another accepted characteristic of the saccadic movement is that it may be regarded as a ballistic movement whose trajectory, once begun, cannot be influenced. Voluntary effort or practice, for example, will not alter saccadic velocity (Becker and Fuchs, 1969; Komoda, Festinger, Phillips, Duckman, and Young, 1973; Westheimer, 1954). The velocity of the eye in a saccade has been carefully studied. The velocity rapidly rises during the saccade to a maximum which occurs shortly before the midpoint of the movement, then drops at a slightly slower rate until reaching its target region. The peak velocity reached is a monotonic function of the saccade length. If the target, say a spot of light, is shifted to a new position while the eye is in motion, no compensatory change occurs in the trajectory. Rather corrective movements are made once the eye finishes the initial saccade. (Westheimer, 1954).

The studies just described support the notions that visual input during reading occurs primarily, and perhaps entirely, during the fixation, and that the saccade is directed by a flight plan established prior to its launching rather than by any visual input during its tenure. Thus, the only visual information which might influence the saccade is that acquired on prior fixations.

Turning now to the questions initially stated in this section, it is safe to say that there is less evidence available on the nature of eye movement control during reading than there is on the size of the perceptual span. Still there is some evidence and much speculation about this. In the following discussion, we will deal first with the control of fixation locations, and then with fixation durations.

The explanations of control of fixation locations appear to fall into three categories, with some explanations involving more than one of these categories. These categories will be referred to as the constant pattern explanation, the stimulus control explanation, and the internal control explanation.

The constant pattern explanation asserts that the reader simply moves his eyes across the page in a uniform manner, sometimes overshooting or undershooting the average distance, on each saccade. A number of people have emphasized the importance of rhythmical eye movements, i.e., regular forward movements along a line of print with about the same number of fixations from line to line (Taylor, 1966; see the reviews by Tinker, 1946, 1958). These people seem to have accepted a constant pattern position. They emphasize the notions that a good reader is efficient because he is able to establish rhythmical eye movement habits and that favorable typography fosters rhythmical movements. According to this position, the eye is simply under physiological and oculomotor control, and it is the task of the reader to process the text as the eye makes its mechanical movements across the page. The poor reader is distinguished from the good reader because he has not developed good oculomotor control. The only specific control assumed might be an adjustment of saccade length for reading materials of different difficulty level.

The original version of this position suffered a substantial blow when it was found that training people to be more regular and rhythmical in their eye movements did not lead to increased reading efficiency and/or comprehension (Tinker, 1958). Without assuming that regularity in eye movements produces good reading, several recent researchers have argued once again for a constant pattern of eye movement control. Carver (1974) dubbed this "apping", taking letters from the phrase "automatic pilot for prose." Bouma and deVoogd (1974) showed that subjects could read when the visual stimulus was presented in a manner simulating rhythmical eye movements.

A closely related position is one which assumes a great deal of randomness in eye control. This might be thought of as a constant pattern explanation with a random oscillatory component as part of the eye control mechanism. This position has been explicitly stated by Bouma and deVoogd (1974) who argue that it matters little just how far along the line the eye is sent on a saccade during reading; thus the only requirement is that the eye is advanced at proper intervals.

The constant pattern explanation is easy to accept as one reviews the many summaries of eye movement data which have been reported, describing the average saccade length and fixation duration of readers of different types and ages. However, an examination of the raw data of even good readers shows such great variability in eye movement behavior that the present authors find this position difficult to accept. Though the mean saccade length may be 8 or 9 character positions, the data values frequently range from 2 to 18 character positions or more. Though the mean duration of fixations may be 1/4 second, the data values actually range from 1/6 to 1/2 second, with occasional fixations as long as a full second or more. It seems to us difficult to conceive of this great variability in saccade lengths and fixation durations as being the product of inaccuracy of the oculomotor system as it attempts to generate a standard, rhythmical eye movement pattern. Whether this variability can be accounted for purely on the basis of random variability in saccade length will have to be tested in further research. Any findings of regularity in saccade lengths will challenge this position.

The second explanation of eye position guidance in reading is that the eye is under stimulus control. According to this position, the movements of the eye are determined by visual characteristics of the text. Information acquired in the peripheral areas of vision cause the eye to be sent to a particular location on the next saccadic movement.

A considerable amount of data collected on eye movements in non-reading tasks is generally supportive of the stimulus control position. Studies dealing with the free viewing of pictures indicate that viewers tend to fixate on the most informative (non-redundant or unpredictable) areas (for instance, Mackworth and Morandi, 1967). According to workers in this area, peripheral vision serves the function of processing and editing out the redundant stimulus. It is generally thought that foveal vision is reserved for those elements containing information needed by the observer during perception, while the peripheral retina screens out the predictable aspects and guides the eye to the unpredictable and unusual stimuli (Mackworth and Morandi, 1967; Mackworth and Bruner, 1970; Yarbus, 1967; Buswell, 1935).

Further data from other types of studies also point out the functional utility of the peripheral retina. Gould and Schaffer (1965) utilized a scanning task with numeric displays and concluded that the more easily seen aspects of a stimulus field are detected with equal accuracy either in the fovea or in the periphery. They also concluded from the data that when more difficult items are initially detected in the periphery, the eyes are then directed to produce a foveal fixation. In a later study, Gould (1967) recorded eye movements while subjects scanned for target patterns. He found that some patterns were correctly recognized without foveal fixation; they were discriminated peripherally. From his findings Gould concluded that a function of peripheral detection is not only to indicate the locus of the next fixation but also to signal whether or not a particular pattern requires foveal fixation.

Hence, studies involving visual tasks other than reading give credibility to the notion of stimulus control in reading. It should be pointed out, however, that although these tasks are like reading in some ways, they differ in others. In viewing pictures, the eye is guided to areas of greater visual complexity. In reading, however, the stimulus pattern is of very similar complexity within the region where text is present. Thus, there is no simple correlation between the visual complexity of the stimulus and its potential informativeness, as there is with pictures. With the scanning task, where the specific target stimulus is known, purely visual characteristics of the stimulus pattern can again be a guide to the potentially informative regions; that is, letter strings having certain gross visual characteristics are more likely candidates as the target than are other letter strings. As one reads, however, the important aspects of the stimulus are the syntactic and semantic characteristics encoded by the physical stimulus. Thus, a decoding is required to obtain the important information. This being the case, either some decoding of the peripheral stimulus for syntactic and/or semantic information must occur, thus yielding an indication of where the more important information is likely to reside, or else some basis for a correlation between aspects of the physical form and the potential informativeness of areas of text must be described. Kolers and Lewis (1972) have argued against the first of these possibilities, that of decoding of peripheral information. They pointed out that such a position would seem to require parallel decoding of information from two regions of the visual field, the normal decoding for meaning of foveal information, and the decoding of peripheral information for the semantic or syntactic information necessary to determine where to send the eye. Their experiments test the notion that the reader could render a semantic decoding of letter sequences arriving at two locations on the retina at the same time. Their subjects were unable to do this. Though these experiments were sufficiently unlike normal reading that they cannot be taken as providing a final evaluation of this position, they do provide some evidence against it. Another experiment might be seen as providing some information for this position. Mehler, Bever and Carey (1967) report that the skilled readers who served as their subjects tended to fixate the first half of phrase structure constituents more than the second half. Problems with the experiment itself suggest that this finding needs to be replicated before it is accepted as reliable. However, if reliable, it might be suggested that eye guidance follows some syntactic analysis of peripheral information. An alternative explanation will be offered later, however.

If it is to be assumed that purely visual aspects of the text in the periphery might be used for eye guidance, without the assumption of semantic or syntactic decoding, it is necessary to find some existing correlation between these visual stimulus characteristics and characteristics important in the processing of the text for meaning. The most simple possibility would be that longer words tend to be more informative, assuming that articles and function words tend to carry little of the information in the text. The hypothesis that the reader might tend to fixate longer words more than shorter was investigated by Woodworth (1938), who reported a slight relationship in the opposite direction: short words received more fixations. Another possibility is that the word length pattern provides strong cues to the location of phrase structure groupings in the text, since phrases frequently begin with shorter words (prepositions and articles, primarily). The present authors have explored this possibility to some extent, and found that college students are able to mark the boundaries between phrases quite successfully in text in which all letters have been replaced by X's. Thus, from the word length and punctuation patterns alone, much syntactic information is given. It may be that the word length pattern is obtained from peripheral vision, which yields some likely syntactic information of coming text, and that this in turn is used to guide the eye.

The distinction between presence and absence of text in an area is undoubtedly acquired from peripheral vision and used to determine whether the next saccade should be to the left or right, and to send the eye past areas which may be blank (Abrams and Zuber, 1972). Thus, to this extent stimulus control is undoubtedly correct. The extent to which the entire eye movement pattern can be accounted for on this basis remains to be seen.

The final type of explanation of eye position guidance in reading is that the eye is under some form of internal control, rather than strictly stimulus control. This position is differentiated from the constant pattern positions in that the movement of the eye is thought of as being determined by momentary internal states, rather than being a simple rhythmical pattern. Thus, irregularities in fixation durations and saccade lengths are the product of internal state differences, rather than just random deviations. Geyer (1968), for instance, has suggested that the eye-voice span (the distance that the voice trails the eye in oral reading) is a constant such that the eye is always ahead of the voice by a certain amount of time. By extension it could be suggested that in silent reading the eye strives to stay ahead of the semantic interpretation of the sentence by a certain amount. Thus when semantic decoding difficulty is encountered fixations are lengthened and/or saccade lengths are reduced in order to keep the eye from getting too far ahead. One data pattern which would support this position would be a strong relationship between the duration of a fixation and the length of the saccade prior to or following it, assuming that when difficulty is encountered both longer fixations and shorter saccades are used to slow the eye's progress. Reder (personal communication) has analyzed a number of eye movement records to determine these correlations, and has found them to be very low. This does not, of course, disprove this particular theoretical position, but it does complicate it in that fixation durations and saccade lengths do not appear to be determined by the same mechanisms. Thus, the separate adjustment of fixation duration and saccade length must now be explained.

A number of writers have emphasized the part which expectancy or prediction plays in reading (Hochberg, 1970; Levin and Kaplan, 1970; Goodman, 1970). Some of these have suggested another possibility of internal control of eye movements. The notion is that the reader, on the basis of the text he has already read and his knowledge of language roles and common usage, is able to predict what is likely to come next. His next task is to acquire that visual information which can most effectively be used to test the accuracy of his prediction. Presumably, on the basis of his prediction his eye is sent to that region of text which is expected to be most informative in acquiring visual information necessary to make this test. If the prediction is inaccurate, the eye is likely to be sent leftward in a regressive movement to determine if an incorrect interpretation of earlier-encountered text was made. This position will be discussed more fully in a later section. At this point it is sufficient to indicate that there is no conclusive evidence to support this mechanism as being the basis of eye guidance, and that the required experimental research necessary to provide an adequate test will be extremely difficult.

Various combinations of these three sources of eye guidance are also possible within a single theory. Hochberg (1970) proposed that eye movement control involves both peripheral search guidance (PSG) and cognitive search guidance (CSG). In agreement with many others, he argues that due to language redundancy the reader need not see every word in order to understand the text. Because of his knowledge of the spelling, grammar and idiom of the text he can anticipate the message. Thus visually he needs only to sample the text to confirm his guess. This is the cognitive search guidance (internal control). In addition, peripheral visual input can be the basis for informed guesses about where the important words can be found, and thus can also be used to direct the eye to those regions which will be most informative in testing his expectations. This is the peripheral search guidance (stimulus control). Hochberg suggests that the main peripheral cues are the initial letter of a word, word length and spacing between words. Of greatest importance is word length. Shorter words are usually functors like "on, in, to, etc." He suggests that the reader is able to detect that a functor lies at some distance out along the line of text in the periphery, and then decides either to look at the word or, if it is likely to be redundant, to look at the word after it. He cites a study by Hochberg, Levin and Frail (1966) as support for the importance of word length and interword spaces in guiding the eye. They had beginning readers (1st and 2nd grade) and more advanced readers (5th and 6th grade) as subjects, and had them read stories typed normally or with all spaces filled in. Having spaces filled had only a slight effect on beginning readers, who were still presumably looking letter by letter and had little knowledge of orthographic and syntactic redundancies. Better readers, who are able to direct their gaze more selectively on the basis of their knowledge of the redundancy of text, showed a substantial reduction in reading rate when spaces were filled. It should be pointed out, however, that the study just cited does not indicate where the locus of the problem is when spaces between words are filled; whether this is disruptive to the eye movement mechanisms, for instance, or whether added processing is required to identify the location of words. Of course, the answer may be that both types of interference are occurring.

While there is little conclusive information on the nature of eye position control in reading, even less consideration has been given to the control of fixation durations. It has been noted that average fixation duration tends to increase with more difficult reading material, and also that the data frequently reveal particularly long fixations on unusual words, proper names, numbers, etc. (Woodworth, 1938).

As with eye position control, it is possible that the control of fixation durations might be either an attempt to follow a rhythmic pattern, with deviations around the average duration being simply due to inaccuracy in the control system, or the length of each duration may be determined in some way by the cognitive processes taking place at that time. The great amount of variance in fixation durations of a single subject reading a single passage argues against the rhythmic pattern position, as does the finding of long fixations on particular types of content in the passage, as mentioned above.

The alternative position, that fixation duration is determined by the perceptual and cognitive processes occurring at the moment, introduces the requirement of very rapid processing of the text being fixated during a fixation. Certainly, some time lapses between the time a saccade is called for and the time it is actually initiated. Sufficient processing of the input must occur early in the fixation period to provide the basis on which to decide when to terminate the fixation (as well as, perhaps, where to send the eye next). Thus, this position would not allow much lag between input and processing of that input for syntactic and semantic information. Different theories of reading assume different types of activities during the fixation, and hence would provide different bases on which the decision might be made to terminate a fixation. At present there is little evidence to select among these. However, if further evidence indicates that fixation durations are under the momentary control of cognitive processing activities, these data will be valuable in discriminating among the different theories of cognitive processes involved in reading.

Peripheral Cues in Reading

As seen in the last section, considerable interest has focused on the possible role of peripheral visual information in guiding the eye in reading. It is possible that this peripheral information may be useful to the reader in other ways as well. This section will explore this possibility.

In order to see a stationary stimulus with the highest degree of acuity, a viewer must move his eyes so as to place the image on each fovea (Schiffman, 1971). The fovea is a very small region, subtending an angle of only about 2° as compared to the retina as a whole which covers a visual angle of 240° (Llewellyn-Thomas, 1968). The foveal retina contains a large quantity of cones. Anatomically and functionally, the distribution of cones has been linked with acuity so that maximal resolving power occurs at the fovea, where the distribution of cones is greatest, and diminishes toward the periphery (Schiffman, 1971). The peripheral retina is very effective in conditions of poor illumination and is very good at detecting movement. Most authorities hold that visual detail is not possible with peripheral vision. However, a number of studies reviewed in the preceding section have indicated that the peripheral retina is utilized in scanning tasks and viewing pictures.

Recently, Kerr (1971) has challenged the notion that visual acuity in the peripheral retina drops rapidly within 5° of the center of the fovea and then continues to drop at a slower rate out to the far periphery. He obtained results indicating that previous findings had underestimated the acuity of the periphery;

that is, the person seems to be able to obtain more visual detail in the near periphery than previously believed. Schiffman (1971) attributes these high acuities to improvements in the control of experimental conditions of assessing acuity. Thus, although there is a definite loss of detail in peripheral vision, still certain characteristics of the stimulus are represented in some detail which are useful in examining pictures and in scanning, and which might be of use to the reader.

Besides its use in directing eye movements, peripheral visual information might be of use to the reader in two ways. First, in the near periphery there may be sufficient detail to permit the identification of words and meaning. Second, the information acquired may be of use in reducing or directing processing on future fixations.

As a stimulus is moved into the periphery, the first information to be lost is the detailed features of internal letters in a word; that is, those letters not bounded by spaces. Still, extreme letters may be identifiable, as well as such aspects of the text as the location of letters having ascending and descending parts, general word shape, word length patterns, and such irregularities as punctuation marks, italicization, underlining, etc. Some of this information can be the basis for word identification, especially in a situation where there is a good deal of redundancy.

Neisser (1967) has pointed out that in the tachistoscopic identification of words, overall word shape is a useful cue. Woodworth (1938) also gave detailed consideration to this notion. Words like lint and list have the same general word shape, while line and lift do not. When words are printed in capital letters, thus having the same rectangular shape, they are harder to identify than when presented in lower case type (Neisser, 1967). Studies by Havens and Foote (1963, 1964; also Foote and Havens, 1965) found words like lint, whose distinctive shape is shared by many other common words in the language, have higher recognition thresholds than words like drab that do not have as many shapemates. They concluded that subjects first identify the shape of a word presented tachistoscopically, and then produce the most common word which is compatible with that shape.

Initial and final letters of words, because they are partially free from masking by adjacent letters, are thought to stand out clearly from the other letters and hence be a valuable cue for both tachistoscopic word identification and normal reading. Marchbanks and Levin (1965) presented pseudoword trigrams and quingrams to beginning readers. They found that the first letter of a word was the most important cue to word recognition, the last letter was the second most informative cue, and word shape was the last used cue. Williams, Blumberg, and Williams (1970) have replicated Marchbanks and Levins' finding with beginning readers, but found that adults used complex strategies including the use of word shape as a basis for word recognition. Levin, Watson, and Feldman (1964) have also argued that the initial and final letters of a word provide the most important cues for the recognition of a word. A number of tachistoscopic letter string identification studies (Bruner and O'Dowd, 1958; Harcum and Jones, 1962; Crovitz and Schiffman, 1965) have reported a bowed serial-position effect when letter strings were presented left or right of the central point of fixation indicating the greater identifiability of initial and final letters. In addition to the initial and terminal letters, dominant letters (letters that extend above and below the line and capitals) have often been thought to be important in word recognition (Woodworth, 1938).

Thus, it appears quite possible that enough visual detail is available from words falling in the near peripheral areas of vision to permit normal reading to occur, even when full visual detail is not available. Those characteristics of the visual pattern which are available may be sufficient to test hypotheses or identify words or meanings under conditions of high textual redundancy. How far into the periphery the reader can identify words or meaning likely depends on the nature of the language constraints at that point, and the particular words involved (such as whether there are several alternative words having the same general shape or extreme letters which would fit the syntactic and semantic context, or only one).

A second way in which peripheral cues may facilitate reading concerns the interaction of perceptual representations of the text from one fixation to the next in reading. Much has been made, recently, of the effects of masking a visual stimulus, and the destructive effects which this has on its perception (Haber and Hershenson, 1973). And it is certainly true that when the eye moves and fixates a new location, the new stimulus pattern overrides the retinal activity pattern produced by the prior fixation. However, we would suggest, with J. Mackworth (1972), that at a higher level in the perceptual processing system the visual information from the two fixations are brought together into a single representation of the stimulus. That is, the visual information from at least two, and perhaps more, fixations is integrated into a single representation. This will be referred to as the Integrative Visual Buffer. Thus, while at one level of perceptual processing masking may occur as the input from one fixation overrides the image from the prior fixation, we assume that at a higher level the information from the two fixations are integrated. This is possible, of course, only because the input from the two fixations is capable of being integrated; i.e., there is sufficient commonality of pattern that they can be justified with one another. This justification of the two patterns may be based strictly on their commonality, or it may be that the eye movement is critical, particularly knowing about how far the eye has been cast. If the visual patterns from the two fixations are entirely different, then masking would be expected to occur at this higher level as well as at the lower perceptual level. It should be stressed that the integrated image is a highly complex one, providing visual information about a number of full lines of text, the book or paper on which the text is printed, the stimuli around the book, etc. A great deal of detail is available concerning some of the region, much less about other areas. Probably sufficient detail is available from several lines of print, and for some distance on each, to permit reading if so desired. Thus, the integrated image should not be regarded as a representation of only a few words on the line being read.

The visual input from each fixation will have its own region of greatest visual detail. Thus, when the pattern from fixation n - 1 is integrated with that of fixation n, in some areas of the representation added detail will be provided over that previously available. However, in these areas, some detail was available before, but just not as much.

It is further supposed that in the Integrative Visual Buffer the representation of the stimulus is still entirely a visual one. Essentially this representation provides a very large set of visual features which serve as a source of information for further cognitive processes involved in reading. Thus, by an attention type mechanism, the reader selects visual detail from a specific region of the total representation which will be used for his reading purposes, whether to identify words or meaning or to check hypotheses. The detail available in the region being attended depends, of course, on the distance of the corresponding region of text from central vision on the last one or two (or few) fixations. If that region was centrally fixated on the last fixation, full visual detail is available.

As reading occurs during a fixation, it would seem reasonable that the reader might not know how far from the point of present reading the available visual detail will support accurate reading. This can be determined only by attempting to read. It is likely that many attempts to read, and perhaps the attempt made on every fixation, extend far enough into the area of peripheral vision that reading fails for lack of visual detail. This means that some processing has been carried out involving the visual features of the text from a given region, but that with the lack of visual detail available ambiguity still remains. Presumably the eye would, on the next fixation, be cast further along the line, thus providing added visual detail from that region, and further processing could proceed. This raises a question: When the reader moves his eye, and the same region is still within the range of his perceptual span, but this time more centrally fixated, must the reader reprocess the text from that region, or is he able to begin the new processing at the point where processing was previously forced to terminate due to insufficient visual data? If the latter is the case, the information obtained from the periphery on the prior fixation(s) will facilitate processing on the present fixation because some of the work has already been done.

Thus, it is suggested that visual information about text falling in the near periphery may facilitate the further processing of that same text when it is later centrally fixated. Some of the visual information about the text needed for its word or meaning identification has already previously been obtained, and on the next fixation, the reader need only obtain the added detail required for its specification, or for testing the hypothesis.

As mentioned above, we do not know how long the information from a fixation remains present in the Integrative Visual Buffer, that the visual data deteriorates fairly rapidly is suggested by the existence of regressions. If full data from the last five or six fixations were present in this buffer, the reader would not have to physically cast his eye backward to gain added visual detail concerning a part of the text recently read. Thus it may be that the visual detail remains in this Buffer for less than a second; that is, that the buffer contains data from only the last one or two fixations, in addition to the present one.

At present there is little data available concerning perception in reading that is specific enough to provide a test of these notions.

Theories of Reading

As the resurgence of cognitive psychology has inspired interest in reading during recent years, so it has stimulated a number of theories about the nature of the cognitive processes involved in reading. Most of the recent theories which attempt a detailed description of cognitive processes involved in reading can be separated into two categories, based on the nature of the cognitive activities which are assumed to be carried out during the fixation. These will be termed the Hypothesis Position and the Direct Perception Position.

A number of people engaged in experimental studies of reading have recently advocated models of reading patterned to some degree after the analysis-by-synthesis theory of speech perception (Jakobson and Halle, 1956; also see Neisser, 1967). This approach, the Hypothesis Position, assumes that reading is primarily an activity of generating hypotheses or guesses about the text yet to be encountered, and then using a small part of the visual detail available to check the accuracy of these hypotheses. (For example, see Goddman, 1968, 1970; Hochberg, 1970; Kolers, 1970; Levin and Kaplan, 1970; Wanat, 1971). On the basis of the information the reader has from reading a passage up to a given point, plus the knowledge he has about (1) the redundancy and rules of language, (2) common language usage, and (3) the topic being discussed in the passage, he generates a hypothesis of what will be encountered next. He then obtains some featural information from the visual display and checks his hypothesis against this information. If the visual information agrees with his hypothesis, as it is assumed usually occurs, he then repeats the cycle. If it is not in agreement, further processing is required, the nature of which varies with different theories. The reader may be thought of as then generating additional hypotheses which are also tested (a pure analysis-by-synthesis approach) or he may be thought at some point to use the stimuli available to directly determine the interpretation of the text. This last process is thought to be much less efficient than the generation and testing of hypotheses, though at some points it must certainly be required, such as at the beginning of a new passage, or when reading words or sentences in isolation. If disagreement between the interpretation of present and past text occurs, the eye is then sent backward in a regressive movement to find the source of the inconsistency.

The popularity of this model of reading has probably risen from its ability to account for several important aspects of reading behavior. It provides a means for explaining how one can read at rapid rates. Assuming that the bottleneck in reading is the input of visual information and that hypothesis generation occurs very rapidly and accurately, this model accounts for rapid reading by permitting the person to obtain the meaning of the passage with the input of a minimal amount of visual information. This model can also account for reading speed changes with different types of text. The critical variable is the redundancy and predictability of the text; less predictable text results in more incorrect hypotheses and requires the acquisition of more visual detail. Finally the model can account for the fact that when misreadings occur they tend to be syntactically and semantically appropriate to the context (Weber, 1970; Kolers, 1968).

In theories taking the Hypothesis Position, then, the reader is thought to spend his time during a fixation, first, in obtaining a small amount of visual detail needed to confirm his hypothesis, and then in generating a new hypothesis concerning what he will encounter in the next region of text which he has not yet encountered. Added activities also might include determining just which aspects of the visual display should be acquired to permit an efficient test of the hypothesis, and perhaps determining how far to send the eye on the next saccade to place it at the region where the visual detail lies which is most important to the testing of his hypothesis. Thus, a relatively small amount of the cognitive activity is involved in perception of the fixated region; more is involved in predicting what lies in the as-yet-unfixated region to be encountered next.

The second category of theories, those taking the Direct Perception Position, assumes that the fixation period is spent primarily in determining the nature of the text within the fixated region, rather than in hypothesizing what is to come. Although those taking the Hypothesis Position have done so primarily in opposition to this position, it appears that the Direct Perception Position can account for the same facts about reading which have been cited as providing evidence for the Hypothesis Position. Consider the following possibility. We know that it is possible for a person to access his memory strictly on the basis of prior information and his knowledge of the language; he is able to take part of a sentence and readily emit words which could reasonably continue the sentence. This is the task he is asked to perform in certain forms of the cloze task and in the sentence-completion task. We also know that he can access memory strictly on the basis of visual patterns; he is able to read a word in isolation. It is reasonable, therefore, to believe that the person can also access memory on the basis of some combination of these two types of information. Thus, as the person reads, he has context information (which alone is not usually sufficient to specify the word or word group to appear next), and he begins, during the fixation, to add to it visual featural information until the combination is successful in specifying a reading for the next segment of the text. At that point, processing terminates for that portion of the text. Of course an incorrect identification may have resulted, but a single interpretation has emerged to which the reader is committed.

This view of processing during a fixation is consistent with the same facts and assumptions which have given credence to theories taking the Hypothesis Position. It provides for rapid reading on the basis of less than complete examination of the visual input. It permits reading to vary according to the redundancy of the text; if the text is less predictable, the contextual information will be less powerful in specifying the words being encountered, and the reader will have to depend upon a more complete visual analysis to acquire sufficient information to specify the text. Since words are being selected on the basis of both contextual and visual information, it would be expected that misreadings would be consistent with one or both of these sources of information depending upon the situation. Thus the model predicts context appropriate misreadings without resorting to the generation of hypotheses or guesses, unless these terms are used in a trivial sense. Finally, the model would allow for regressions during reading. If a wrong identification is made, this leads to incorrect contextual information for making the next identification. Thus, with more and more visual information, it is likely that no identification will be made because of the incorrect context until finally the visual information is sufficient to complete the identification on this basis alone. At this point, the inconsistency between the prior and the new information is detected, and the eye is sent back in a regressive movement to seek the nature of the inconsistency.

The two positions just described differ most greatly in terms of what the reader is assumed to be doing during a fixation. The Hypothesis Position has the reader testing his hypothesis and then generating another. The Direct Perception Position suggests that the reader spends this time in the direct analysis of the visual input available on that fixation, using it together with contextual information to identify the text being fixated. The Hypothesis Position seems to assume that a majority of the fixation time is spent considering text not yet encountered, whereas the Direct Perception Position assumes that most time is spent analyzing the text in central vision.

As this alternative model, of a Direct Perception Position type, has shown, the Hypothesis Position is not required by the available data about reading; other positions are able to deal with the same facts concerning rapid reading. In addition there are some reasonable arguments against the Hypothesis Position as a model of the reading process. For one thing, the proponents of this position have not actually specified what it is the reader makes guesses about. If this model is to account for the fact that misreadings are syntactically appropriate, it would appear that the reader must be making hypotheses about the specific words to be encountered. The technique used by Levin and Kaplan (1970) to assess the redundancy of different parts of sentences, on the other hand, investigated the degree to which people anticipated the grammatical form of the sentence. This might suggest that readers form a hypothesis about the grammatical form. Another possibility might be that the reader, from his prior knowledge of the topic being discussed, anticipates the general argument or description which is to follow, without necessarily knowing the specific words in which it will be communicated.

The last two possibilities, anticipation of grammatical form or of the general meaning, seem to lose some of the characteristics of the Hypothesis Position. Since the hypothesis of syntactic form does not lead to predictions of the specific words to be encountered, it is difficult to see how it could account for the syntactic and semantic appropriateness of misreadings. The words which are emitted must be selected on some other basis than the hypothesis itself, if the hypothesis is not assumed to be an anticipation of the words to be encountered. Thus, the model would seem to resort to the direct perception of visual features to select words. At this point, the distinction between the Hypothesis Position and the Direct Perception Position becomes fuzzy. Both assume the use of a combination of contextual and visual information to specify the words to be read. Just what part a hypothesis might play in the process is not clear unless it simply permits the words to be identified with fewer visual cues. If this is so, the Hypothesis Position and the Direct Perception Position become indistinguishable. Once this has occurred, it leaves one wondering what is gained by proposing a hypothesis-generating mechanism in the reading act; it seems sufficient to assume that words are accessed on the basis of both contextual and visual information.

On the other hand, if the hypothesis is assumed to be an anticipation of the meaning of the message, one might suppose that it is possible to go from text to meaning directly, without the necessity of individual word identification. This position would suppose that the reader anticipates the meaning of the passage, and then is able to check the accuracy of that meaning against the input of a relatively few visual features. Again this seems to present some serious problems. As the linguists have stressed and particularly Chomsky (1965) with his transformational grammar, a given meaning can be expressed in a large number of word combinations and arrangements. Thus, it seems unlikely that any meaning which requires a combination of words to be expressed, other than such common combinations as "alarm clock" or "Holy Bible", has any invariant set of visual features in the text associated with it. There would seem to be no small set of visual features which could be tested to determine whether a given meaning matches the expressed in the text, without consideration for the words and their arrangement in the text. If this is so, the testing of the accuracy of a hypothesis of meaning must necessarily be mediated through some amount of word identification; either the hypothesis must indicate what words to expect so the reader can use visual features to test the hypothesis directly, or the reader must use visual features to determine what words are present in the text, and their order, so he knows what particular word string was used to express the meaning he anticipated. In the first instance, the hypothesis returns to that of word anticipation. In the second, the position is subject to the same problems as the syntax-hypothesis position and becomes indistinguishable from the Direct Perception Position.

It appears, then, that for the Hypothesis Position to be effectively based on a hypothesis-then-confirmation cycle as a mechanism for reading, and to be distinguishable from the Direct Perception Position, it must be assumed that the reader anticipates the actual words of the text to some degree. Only then is the expected visual form sufficiently concrete that it would be possible to sample a small set of visual features and on that basis determine that the hypothesis was accurate or not without using the visual information for word identification in the process. However, this encounters another problem. Although much has been written about the great amount of redundancy of language, it is still true that if a person reads a passage up to a given point and then attempts to guess the next word, he will be wrong far more often than he is correct, for most text. Normal English prose, though quite redundant, is not sufficiently redundant that the next word can usually be anticipated. This suggests that it is not sufficiently redundant to allow a hypothesis model of reading, based on anticipating words and then simply sampling the visual input to confirm the hypothesis, to work. It is interesting in this regard that the computer programs that have been at all successful in understanding language have not used an analysis-by-synthesis approach (Winogard, 1972).

Finally, the Hypothesis Position makes some very strong assumptions that are seldom expressed. It assumes that the bottleneck in reading is the visual input process. The generation of hypotheses must be much faster than the act of taking in visual information and using it to identify the words or meanings of the text, else why not simply look to see what the stimulus is rather than hypothesize about it. This assumption does not seem to be obviously correct. Another assumption already mentioned concerns the degree of redundancy in the language.

In summary, then, the model which we find most useful is based on the Direct Perception Position. It assumes that the reader, at the beginning of a fixation, has contextual (syntactic and semantic) information which can be used to access his memory store. Visual detail is acquired at the beginning of the fixation, and is integrated with similar detail from prior fixations in the Integrative Visual Buffer. Visual featural data is taken from that buffer, according to where the reader is in his reading, and is used for the cognitive processing operations involved in identifying the meaning of the text.[1] As these data are selected they are added to the contextual information already available. At some point, this combination of information is sufficient to specify the words and/or meaning of the text in this region. Thus, the amount of visual information required depends on the amount of redundancy in the language at this point. If an error is made in identification, this may lead to a regressive movement on some later fixation, if the error provides a context in which later words are inappropriate.

This model further assumes that the reader has available to him different degrees of specificity of the visual pattern at different distances into the periphery. Since only some visual information is needed to identify the text, the reader is able to make this identification further into the periphery than he is able to obtain full featural detail; how far depends on the language redundancy at that point and on the visual similarity of alternative appropriate words. This leads to the suggestion

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1. Brown (1970) has suggested a "noticing order" of cues for a word which may represent the order in which visual data is taken from the Integrative Visual Buffer: first word length and possibly general shape, then first letter, next final letter, and finally visual detail of internal parts of the word.

that saccade lengths may be governed to some degree by the distance into the periphery in which text identification was possible. Other information from peripheral visual areas, such as word length patterns, may also have an influence. It is further assumed that a new fixation adds visual detail to the Integrative Visual Buffer which allows the processing of the text to continue from the point reached on the prior fixation. Finally, it is assumed that the duration of a fixation is determined by the cognitive activities the reader is engaged in. Thus, points where added activities such as meaning integration processes are required, or where text redundancy is low and added visual detail is required in identifying the text, result in longer fixations. Points where text is highly redundant, where meaning integration cannot be carried out, or where little visual information resides produce short fixations.

CHAPTER 2

OVERVIEW OF THE RESEARCH

The series of experiments to be described in later chapters was undertaken to investigate how far into the periphery different aspects of the visual stimulus are acquired during a fixation and used by skilled readers in their reading. The data obtained also provides some information on other questions as well, dealing with eye guidance, the use of peripheral information in reading, etc.

The primary contribution to the psychological investigation of reading which this research has made was technological. A new technique was developed for studying reading which opens the door to the investigation of many specific aspects of the perceptual and cognitive processing in reading. This technique has two parts: computer monitoring of eye position during reading, coupled with computer control over the display from which the person is reading.

This chapter will first present a general description of the computer techniques employed in the research, and will then provide a brief overview to the studies to be reported in later chapters.

The Computer Techniques

A computer program was developed which sampled the reader's eye position at frequent intervals (60 times per second). The equipment used required that the reader's head be immobilized by means of a bite bar and forehead rest. After the eyetracking equipment was adjusted, and the reader went through a calibration sequence of looking at each of a series of points and pushing a switch as he fixated each one, the computer was able to determine the reader's direction of gaze. The computer calculated the amount of movement of the eye during each sixtieth of a second and, on that basis, was able to detect when the eye initiated and completed a saccadic movement, and where the eye was directed during a fixation. Eye position was registered in terms of the line of text and character position on that line which was in central vision. Accuracy of the system was assessed by asking the subject to fixate a series of points and then seeing what locations the computer indicated that he was looking at. The computer-indicated position was essentially always within three character positions of the target position; it was practically always within two character positions of the target.[2] We do not know, of course, how much of the variability obtained was due to inaccuracy in the equipment, and how much was due to variability in the eye itself; successive attempts to fixate the same character undoubtedly do not place the eye in exactly the same position.

With this system, the computer knew at each eye position sample the distance traveled since the last sample, and by comparing this with a threshold, declared the eye to be moving or still. Thus, on a moment-by-moment basis the computer knew the state of the eye, its velocity of moving, and what area of the page was in central vision if still. It was programmed to keep records of the location and duration (in sixtieths of a second) of each fixation, and the time required for each saccade. These data represented a complete record of eye movement behavior in reading a passage, and were in a form to be readily analyzed by other computer routines.

The second part of the technique used in this research involved computer control over the display from which the person was reading. Subjects read from text displayed on a Cathode Ray Tube (CRT) under computer control. This CRT permitted the display of 40 lines of 80 character positions each, though in the experiments only 3 to 10 lines of text were actually displayed at once. As with television, the image on a CRT fades very rapidly and must be constantly refreshed by the computer. Around 60 or more times a second, the computer refreshed the image on the CRT in order for it to have a steady (non-flickering) appearance to the observer. With this equipment, it was possible to very quickly change the display. If the computer instructions for the display were modified by the computer itself during the fraction of a second existing between two successive refreshes of the CRT, a change in the display was immediately produced, since on the second refresh a different image was drawn on the CRT. It was possible to change the image sixty or more times per second if desired. Thus it was possible to make very rapid changes in the text as the person was reading from it. The time required to do so was less than the time occupied by a single eye movement from one fixation to the next.

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2. In this paper, eye position will typically be indicated in terms of the line fixated and the character position on the line. Visual distance will also be reported in number of character positions. On the CRT display, each character occupied a constant amount of space on the line, whether the character was a letter, a punctuation mark or a space. The size of the display was such that there were about four character positions to each degree of visual angle.

Since the computer which was in control of the display was the same one which had moment-by-moment information on the eye position and movement status, it was possible to write programs which made display changes based on the location or movement status of the eye. Thus, it was possible to produce a change in the display when the eye made a saccade; thus on the next fixation, the stimulus pattern was different than it was on the last fixation. It was also possible to monitor the eye's position during a saccade until it came to rest, and then quickly make a change in the display at the place being fixated by the reader. This change can occur fast enough that the subject has no sense of delay in the stimulus onset; that is, it appeared to him that the change was already made when his eye came to rest.

The system just described, and which is described in detail in the next chapter, introduces a new type of stimulus control to reading research, as well as to research on other tasks involving visual perception. To see the effect of certain stimulus patterns on eye movement or eye fixation data, it is now possible to create those exact patterns and have them occur on a particular fixation, or on each fixation, while the person is engaged in the task of reading a passage. A complete record of eye movement behavior is kept, allowing the experimenter to examine this detailed record for information on the effect of his stimulus manipulations, in addition to getting introspective reports or scores on retention test questions following the reading.

The equipment and computer programs used are described in detail in Chapter 3.

The Studies Conducted

In the research to be presented, the computer techniques described above were employed to provide new data on the old question of the size of the perceptual span in reading. Two different types of studies were carried out, employing different types of stimulus changes during reading. The first four experiments, employing one type of stimulus change, will be referred to as Window Experiments. The final experiment, in which a different type of stimulus change was made, will be referred to as the Boundary Experiment. These two types of studies will now be briefly described.

In the Window Experiments, an attempt was made to manipulate how far into the retinal periphery certain visual characteristics of the original text were present during each fixation. It was assumed that if, during reading, a certain aspect of the visual pattern of the text were normally acquired a certain distance into the periphery, and if that aspect of the pattern were removed from the display or changed in that region, reading performance would show some form of deterioration. This deterioration should be detectable in the pattern of eye movements made by the reader. As an example, under one condition two versions of a page of text were prepared, one containing the normal text, and the other containing a pattern in which each letter of the original text was replaced by the letter x. This second version will be called the peripheral text pattern. Though being totally unreadable, it did maintain certain visual characteristics of the original text, such as word length patterns, punctuation, and capitalization. The peripheral text pattern was initially displayed on the CRT. However, when the reader made his first fixation on the first line of the text, the computer immediately replaced each x within a previously-defined distance to left and right of the fixation point on the first line with the corresponding letters from the original text. Thus, during that fixation there was a region of normal text for the reader to see, called the window. When the reader made a saccadic movement, sending his eyes to a new location, the letters in that window were replaced by x's once again, and a new window of normal text was created at the point of the next fixation. Thus, wherever the reader looked, he was able to see the normal text that existed at that location, so he was able to read quite normally. However, the experimenter was able to control the size of the window, and to observe the effects of window size on the reader's eye behavior pattern as he was reading. An example of the type of display that might be present on the CRT during a single fixation, is shown in Figure 1.

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Fig. 1. Example of the display during a single fixation in a Window Experiment. This display was seen by a subject fixating the letter *e* in the word *the*, and reading with a window size of 17 character positions. The original display had seven lines of text.

Another peripheral text pattern was also created for the same text in which not only letters, but also spaces and punctuation marks were replaced with x's. Thus, in this pattern, punctuation and word length information were deleted. If the first of these peripheral text patterns were displayed as the subject was reading, word length information was available to his visual system in the region beyond the window. If the second pattern were displayed, this information was not available beyond the window. Subjects were asked to read text silently under these two conditions, and with windows of different sizes. It was expected that with a very large window, it would make no difference to the reader whether the peripheral text pattern contained word length information or not; he was able to obtain that information from the region within the window for as far into the peripheral visual areas as he normally acquired it in reading. However, as the window became smaller in size there would be a point at which it extended less far into the periphery than the reader normally acquired word length information. At that point, reading would proceed more smoothly when the peripheral text pattern contained word length information than when it did not, since the visual information he normally used in reading was still present in that pattern whereas it was not in the other. Thus, it was deemed possible to determine how far into the peripheral visual area the readers were acquiring word length pattern information and using it in their reading by determining how small the window could be made before reading behavior was affected by the presence or absence of this information outside the window. This same strategy was used to explore how far from central vision the readers were acquiring general word shape information. These studies are reported in Chapters 4 and 5. Chapter 6 describes a study investigating whether subjects appear to acquire certain visual information from the line below the one they are directly reading. Chapter 7 reports the last of the Window Experiments, designed to determine whether the region from which these aspects of the visual pattern are acquired is symmetric around the point of fixation.

Chapters 8 and 9 describe a different approach to the investigation of the perceptual span, one which involves minimal display change. This is called the Boundary Experiment. It was based on two assumptions: first, that visual information is integrated across fixations, and second, that if visual information obtained on one fixation does not correspond to that obtained on the next, added processing is required of the visual input which will be reflected in a lengthened fixation duration. In this study, a single word position in each paragraph was identified as the critical word location (CWL). A boundary was set prior to that location on the same line. When the eye crossed the boundary, this triggered a display change in the CWL. As the person began reading, the stimulus displayed in the CWL was a word or letter string having some particular similarities or differences to the Base Word which normally occupied that location. This initially-displayed word was like or unlike the Base Word in terms of word shape or first and last (extreme) letters. As the person read, when his eye crossed the boundary, the stimulus initially displayed in the CWL was removed and the Base Word was put in its place. Thus, certain aspects of the visual pattern in that region were different on one fixation than they had been on the previous fixation. The durations of fixations occurring immediately after such a change were categorized according to the type of display change produced, and how far the eye was from the CWL on the fixation prior to the change. Mean fixation durations for each category were then compared to see how far into the periphery there was evidence that specific aspects of the visual pattern in the CWL had been obtained by the reader.

The last two chapters of this report summarize the results of the experiments, discuss their implications for theories of reading, and make suggestions concerning future research using the type of computer-based eye-movement controlled display system developed for this research.

CHAPTER 3

EQUIPMENT USED AND COMPUTER PROGRAMS DEVELOPED FOR THE RESEARCH

This chapter describes the equipment used and computer programs developed for the research to be presented in later chapters. It will deal with six topics: (1) the eye-tracking equipment used, (2) the computer system to which this equipment was interfaced, (3) the computer program developed for conducting the experiments, (4) characteristics of the Eye-Movement Controlled Display System, (5) the computer programs developed for processing the data, and (6) a computer program used to prepare material for the experiments.

The Eyetracking Equipment

The equipment used to monitor the reader's direction of gaze was a Biometrics Corporation, Model-SG Eye Movement Monitor. This equipment uses a photo-electric technique to determine eye position. A small infra-red light-emitting unit is mounted on glasses frames, together with two photo-diodes. These are positioned just below the eye, about 1/4 to 1/2 inch from the surface of the skin. The surface of the eye is bathed with infra-red light, and the photo-diodes are aimed at particular locations of the eye structure, to monitor the amount of light being reflected from those areas. Horizontal movement was monitored from the right eye by positioning the photo-diodes to respond to light reflected from the region of the boundary between the iris and sclera, with one photo-diode aimed at this region on the right side of the iris, and the other on the left side. As the eye rotated horizontally, more of the iris moved into the field of view of one of the diodes, thus reducing the amount of light reflected to it, while more of the sclera moved into the field of view of the other diode, thereby increasing the amount of light reflected to it. Movement in the other direction produced the opposite effect. The electronics of the eye movement monitor (EMM) subtracts the output of one sensor from that of the other, and modifies the signal in other ways, to produce a single output which is quite linearly related to the amount of rotation of the eye on the horizontal plane, with the signal ranging from -10 to +10 volts.

This same technique is not appropriate for monitoring vertical movement of the eye, since for most people the eyelids hide the iris-sclera boundaries on top and bottom. Therefore, the procedure recommended by the manufacturer is to place the photo-diodes for the other eye (in our case the left eye) so they are aimed at the boundary between the eye and the eyelid, either the lower or upper eyelid. We found the lower eyelid to yield the best signal. There is a strong tendency for the eyelids to move in a manner which corresponds to the movement of the eye itself on the vertical plane. Therefore, as the eye moves up, more of the lid enters the field of view of the photo-diodes, reducing the amount of light reflected to them; as the eye moves down, more of the eye itself is exposed to the field of view of the photo-diodes, increasing the amount of light reflected to them. The signals from the two photo-diodes are summed in this case, and again with electronic modification yield an output signal which is fairly linearly related to the amount of movement of the eye. In this case, however, there are many artifacts which interfere with the accuracy of the signal as an index of eye position: blinking and the associated hysteresis of the eyelid, squinting, and some movement of the eyelid with horizontal eye movements, for instance. As will be described later, we were unable to reliably distinguish which line of text was being fixated on the basis of the vertical eye movement signal alone, even with triple or quadruple spacing of the text, so we abandoned the use of that signal and developed a heuristic for determining which line the reader was fixating at any given moment.

Degree of linearity of the signals, and of crosstalk between the signals, were a function of the position of the sensors. Careful adjustment was required, having the subject repeatedly fixate a series of points as the experimenter monitored the vertical and horizontal signals and adjusted the sensors to reduce non-linearity and crosstalk. This adjustment often required 15 to 20 minutes, and was generally quite tiring to the subjects. Two problems complicated this process. First, there seemed to be no clear rules which could be developed to determine from the characteristics of the signals themselves just where the sensors should be moved to improve linearity and reduce crosstalk. Second, the pattern of crosstalk and non-linearity varied so much with different sensor positions and for different persons that it was not possible to develop computer techniques to compensate for these irregularities. It was necessary to depend on adjusting the photo-diodes themselves to minimize most of the non-linearity and crosstalk. Once that was done, final compensation for non-linearity could be accomplished by the computer.

The degree of these problems was, of course, a function of the size of the visual area over which eye movements were being recorded. The displayable area which we had to work with displaced a visual angle of about 18^{0} on the horizontal dimension and slightly less on the vertical. To reduce these artifacts the actual region on which text appeared for the experiments occupied only the upper half or third of the total displayable area, thus placing the text in the region where crosstalk was at a minimum. Also, as will be described later, the programs were written to allow the computer to compensate for much of the remaining non-linearity in the signal.

In order to determine where on a display the person was looking, it was necessary to hold the head in a rigid position, and to hold the sensing equipment steady with relation to the head. Two techniques were used to accomplish this. First, the head was immobilized by the use of a bite bar and a forehead rest. A heavy dental-impression compound was molded onto a brass fixture, and the subject placed this in his mouth and bit into it. When cooled, the compound became very hard. The fixture was fastened solidly to a frame, which was attached to the display. The subject again entered his teeth into the impression made previously, and the forehead rest was adjusted. Once in place, head movement was quite well controlled. Second, in order to hold the sensors steady, the glasses on which they were mounted were fixed to the head, first by a strap around the back of the head, and secondly by an elasticized headband to which the cord leading from the glasses was fixed. With this headband in place, the cord could be bumped or pulled without disturbing the position of the glasses.

The subject sat comfortably with his arms on armrests and with feet flat on the floor or on a box of appropriate height. This was emphasized, since substantial shifts in posture could produce head movement even with the bite bar in use.

When in position, the subject's eye was about 21 inches from the display.

The Computer System

The research to be described was carried out with the computer system of the Artificial Intelligence Laboratory at Massachusetts Institute of Technology. The computer used to conduct the experiment was a Digital Equipment Corporation (DEC) PDP-6, a computer which uses 36 bit words, equipped with 32K words of core memory. This computer was interfaced with a PDP-10 time-sharing system. Both computers shared certain facilities, including A/D converters and a DEC Model 340 cathode-ray tube (CRT) having a hardware character generator for both upper and lower case letters.

The programs for conducting the research resided in the core memory of the PDP-6, but the PDP-10 system was used for file-handling. Thus, the PDP-6 called for text files from the PDP-10, and passed data for filing to it. On the other hand, all data analysis was conducted on the PDP-10 computer.

The CRT had a P-7 phosphor which is actually composed of two phosphors, one of which glows blue-white and has a very short persistence, and the second glows yellow and has a very long persistence. In order to produce crisp display changes, a dark-blue theater gel was used to filter out the yellow image. The result was a display with a blue appearance, and visual characteristics of a P-11 phosphor. With this modification no observable afterglow remained.

The CRT is capable of displaying 40 lines of 80 characters each. The width of this display is about 8 $\frac{1}{4}$ inches and the height about 7 $\frac{1}{4}$ inches. Of the eight intensities available, we used intensity 7, the highest. Only three to ten lines were displayed at once, so the refresh rate was quite high with such a small display. There was no apparent flicker.

Computer Programs for Conducting Experiments and Viewing Data

The computer programs developed for this research have much in common with those described by Reder (1973).

The entire program for conducting the experiments and for viewing certain aspects of the data was written in PDP-6 assembly language and was loaded into the computer core memory at once. This included a Top Level component which initialized the system for the research and then waited for teletype input for jumping to any of the main operating programs. Instructions to Top Level were in the form of single letter commands, which caused a jump to the specified program.

Top Level operated under a modified version of Digital Equipment Corporation's Dynamic Debugging Technique (DDT) which acted as the monitor, and also allowed access to the program for modification.

The major sub-programs available to Top Level were: CALIB, a calibration routine; EYETRACK, the basic program for monitoring eye movements, collecting data, and modifying the display; RUN, a general program allowing advance specification of files and conditions for a particular experiment and which then called CALIB and EYETRACK in their proper sequence for the actual conduct of an experimental session; PLOT, which collected eye movement data as a person was reading and then plotted the data on a Calcomp Plotter; and VIEW, which required the specifying of a text file, a data file, and a set of experimental conditions, and then permitted the operator to step through the data, recreating the form of the display on each fixation, and indicating the number of that fixation, the eye position, and the duration of the fixation and length of the saccade. These programs will now be described in detail.

CALIB. The purpose of CALIB, the calibration program, was to obtain the parameter values needed to identify from the X (horizontal) and Y (vertical) signals from the eye-movement monitor (EMM), where on a display the subject was looking. Basically, it involved having the reader look at a series of points on the display, pressing a lever as he fixated each, and having the computer sample the EMM signals when the lever was pressed. Finally, the data so obtained were averaged to get the parameter values needed later by the eyetrack programs.

The calibration program required two vectors as arguments, one a list of character position values (CPVEC) and the other a list of line numbers (LVEC), in ascending order. These defined a calibration pattern, a series of points at which a target (an asterisk) was to be displayed. The program took the first value from each vector, which defined the first point (line number and character position on that line) where the target was to be placed, displayed an asterisk in that location, and waited for the subject to press the lever. When the lever was pressed, the computer sampled the X and Y signals from the EMM and stored the values in a table. The second value was then taken from CPVEC, and the asterisk was moved to a new position on the line. When eye position samples had been obtained from all specified positions on the first line, the computer selected the second value from LVEC and the first value from CPVEC, displaying the asterisk at the first position on the second line. Finally, when all points in the calibration pattern had been displayed, and the EMM values obtained for each, the values were averaged in the following manner. The Y values for all fixations made on the first specified line were averaged to give a mean Y value for that line. Similar means were computed for each of the other lines specified in LVEC, and were stored in the vector YPAR (for Y Parameters). Then the X values for all fixations made at the first specified character position on all the lines were averaged to obtain a mean X value for that position. Similar mean X values were obtained for each character position specified in CPVEC, and were stored in the vector XPAR (for X Parameters).

The result of this activity was two vectors of means, indicating the mean EMM X and Y signal values corresponding to the display location values in CPVEC and LVEC. These were the parameters needed by the eyetrack programs to identify from the EMM signals where the person was directing his gaze on the display.

In the research to be described, LVEC generally contained 5 values and CPVEC, 6 values, resulting in 30 calibration points.

During the calibration task, a pattern was displayed on the screen which was similar to the general pattern of the displays used in the experiment, except that it was composed entirely of strings of X's. The target used for calibration was displayed between the lines of this pseudo-text pattern, to ensure that the lighting characteristics were as similar as possible between the calibration and experimental tasks. This was found to be necessary since pupil size influenced eye position readings to some degree.

EYETRACK. The EYETRACK program monitored the reader's eye position, identifying the beginning and end of each fixation, recording eye movement data and producing display changes based on eye position when desired.

There were actually four versions of the EYETRACK program which could be called, depending on the letter-command used to call it. These will be referred to as the A, B, C, and D versions.

All versions required parameter values from CALIB which permitted conversion from EMM signals to line number and character position on the display. The A, B, and C also required four parameters specifying the size and location of the window, the region within which normal text was displayed: HITE, which specified the window height in terms of number of lines; WIDTH, which specified window width in terms of number of character positions; XOFSET, which offset the center of the window to left or right of the point of central vision; and YOFSET, which offset the center of the window above or below the line being fixated. Another parameter, THRSH, contained a threshold used to determine whether the eye was moving or still, and a second parameter, THRSH2, was used in the C version to identify when the reader was advancing to the next line.

The B version of EYETRACK will first be described, followed by an explanation of how the other versions deviated from it.

The EYETRACK B program carried out two basic functions. First, it tracked the eye and made a record of eye behavior, and second, it produced display changes based on eye behavior.

To track the eye, the program sampled the EMM X and Y values every 1/60th of a second. The new eye position values were subtracted from the values obtained on the previous sample. If the difference found was greater than the value in THRSH, the eye was declared to be moving; if it was smaller than that value it was declared to be still. When the eye was first found to be moving after at least one interval during which it was still, the program recorded how long (in 1/60th's of a second) the eye had been at rest. When the eye was first found to be still after at least one interval of movement, the program recorded the length of time that the eye had been moving, and calculated where the gaze was directed.

Calculating the direction of gaze was carried out in the following manner. The X value obtained from the EMM, called NEWX, was successively compared with the parameter values in the XPAR vector obtained from CALIB. The first value was found which was larger than NEWX. We will call that value XPAR(N), with N indicating its position in the vector. This identified the subregion which the direction of gaze fell into, the region between CPVEC(N-1) and CPVEC(N). The program then used a linear interpolation to estimate the eye position:

$$\text{Character Position being fixated} = \text{CPVEC}(N-1) + \left[\left(\frac{\text{NEWX} - \text{XPAR}(N-1)}{\text{XPAR}(N) - \text{XPAR}(N-1)}\right)\left(\text{CPVEC}(N) - \text{CPVEC}(N-1)\right)\right]$$

This algorithm assumes that the values of CPVEC divide the display into regions within which the EMM signal is linearly related to the display space. Thus, the first task is to find the region in which the gaze lies. This is done by comparing NEWX to successive values in XPAR until one is found which is larger than NEWX. This indicates that NEWX falls in the region the upper boundary of which is XPAR(N); that is it lies in the nth region. This is the region between CPVEC(N-1) and CPVEC(N). Then a simple linear interpolation is used to determine which character position in that region is being fixated.

Determining the line fixated is carried out in an identical manner, comparing NEWY with values in YPAR, and then interpolating between values in LVEC.

The result of this activity is two values, a line number and character position, which specify the subject's direction of gaze. These values, which indicate the location of the fixation, together with the durations of the previous fixation and saccadic movement, were sent to a buffer for output. Thus, a data block for a fixation-saccade pair consisted of two computer words, one of which contained the previous fixation time and moving time, and the second contained the X and Y values for the location of new fixation.

Display changes were based on the eye position data. The program required two files of text to be in core memory, one of which will be referred to as central text and the other as peripheral text. The peripheral text file was used as the display list. For instance, it might contain a version of the text in which all letters had been replaced by X's, and this was what was displayed on the CRT. However, when the eye was detected as having fixated, and the location of the fixation had been computed, this data was fed to a WINDOW routine which exchanged a series of characters between corresponding positions in the two text files. This had the effect of replacing part of the display list with corresponding characters from the other file which contained normal text. Thus in a certain region of the display, the region being defined with reference to the point of central vision, normal text was visible. The size of this region was defined by HITE and WIDTH, and its location by XOFSET and YOFSET. Thus, if HITE = 1, WIDTH = 13, and XOFSET and YOFSET were both set to zero, this region would include 13 letter positions on the line being fixated, the character being directly fixated and 6 characters to right and left of that position.

This display was not changed, even though the eye may have drifted somewhat during a fixation, until the eye was detected as moving once again, and then came to a stop. At that point the two text files were restored to their original condition, line and character positions for the new fixation were calculated, and these were used to place the "window" of normal text at the next position. Thus, each time the person completed a saccade, the display was changed to place normal text at the position desired. It should be noted that if the same text were loaded into both text files, no visible display change would take place.

In order to make the display changes, the CRT was turned off, the computer then modified the display list in the manner described, and the CRT was turned back on, initiating the scan from the top of the display. The time from the identification of the onset of a fixation until the CRT was turned off was 50 microseconds. The time the CRT remained off was a function of the size of the window; that is, the number of characters that were exchanged between the text files. With 17 characters, the time was 6 milliseconds, a short enough time that no blink in the display was detected. In general an increase of 20 characters in the size of the window added 5 milliseconds to the time the CRT was off. Thus, with a window size of 100, the CRT was off for around 30 milliseconds, which produced a very noticeable blinking of the display.

Each time the computer sampled eye position, it also checked to see if the subject had depressed a lever available to him or if there was teletype input. If the lever had been depressed, the program called for the next page of each of the display files, translated the characters into code accepted by the display system, and set up the central and peripheral text files. If the last page of a file had previously been brought in, and another page were called for, no change was made in the text. If a D were struck on the teletype, the program would send control out of EYETRACK and back to the Top Level.

Finally, a double-buffered data output routine was included to send data to the PDP-10 in blocks of 50 words each time a buffer was full.

As indicated earlier, there were three other versions of the eyetrack program that were prepared for specific purposes. They each used the routines from the program just described, but initialization procedures when the programs were called set up flags and parameters in such a way as to cause EYETRACK to operate slightly differently.

The EYETRACK A routine updated the display with every other sample of eye position. Thus, each 30th of a second the computer calculated where on the display the gaze was directed and modified the display list to place the window of text from the central text file at the specified location. This routine did not collect data. It was used to explore the accuracy characteristics of the system. One means of doing this was to place a file consisting of all asterisks in the central text file, and a pattern with just a few widely spaced numbers or letters in the peripheral text file, and then setting the window size to display a single character in the window. This caused the system to place a single asterisk at the point the computer indicated that the person was fixating. Then the person was instructed to fixate certain of the letters or numbers displayed on the CRT, and the experimenter could see by the position of the asterisk how far off the computer's reading was from where the subject said he was fixating. As previously indicated, it was impossible to determine how much of the inaccuracy was due to unreliability of the eye to position itself identically each time an attempt was made to fixate the same location, and how much was due to failures of the eyetracking equipment and the computer programs.

The EYETRACK C routine was actually used in the Window Experiments to be described later. It was like the B version, collecting data and making a display change at the beginning of each fixation, with the exception that it ignored the EMM signal for vertical movement. Thus, it only took data from one channel, that which indicated horizontal eye movement. It contained a parameter, THRSH2, which contained a value used to determine when a reader had advanced a line. If a leftward eye movement, or series of leftward movements, carried the eye

THRSH2 character positions to the left of the rightmost location previously fixated on the line, it was assumed that the reader had made a return sweep of the eyes and gone on to the next line. For our research, this value was set at 45. Thus, it was assumed that when the reader initially made a leftward movement of more than 45 character positions in length that he was then beginning to read the first line of text. He was assumed to be viewing that line from then on until another leftward movement (or series of movements) of 45 character positions was detected.

To use this routine, a spot was placed on the face of the CRT in the upper right corner of the screen. Subjects were asked to fixate that spot after carrying out the calibration task, and to remain there until text came on the screen, at which point they were to look to the beginning of the first line and begin reading. They were asked to read the text line-by-line, and not to make long regressions or try to look at lines other than the one they were presently reading. When a window of real text was placed on a peripheral text display of pseudo-text, these instructions became rules by which the reader must operate in order to read. That is, the window appeared on the first line only after a long leftward movement. If the reader tried to fixate the first line before the text display came on, no window appeared and he would be forced to look to the right and then to the left again to get the window to appear. The window would follow his eye movements on the line he was reading, but if he made a long regression the window would suddenly drop to the next line, forcing him to go on to the next line in order to read. In addition, if he attempted to look back at a line he had previously read, the window would not follow him, and he would have to return to the line where the window was to continue reading. Subjects were given practice reading with the window, and the way it was programmed was carefully explained to them, so they would understand its behavior. Once the reader understood and had some practice reading with the window (having read two or three 500-word passages) he was quite comfortable with it and seldom attempted to violate the rules by which it operated, or even found it a hinderance to his reading. Still the constraints of the window behavior likely had some effect on his reading, probably causing him to reduce the number of regressions he typically made.

The EYETRACK D routine was used for the Boundary Experiment to be described later. Here, the central and peripheral text files were not used in the manner previously described, switching characters between them to build a composite display. Rather, they served as alternative displays. When the display was first called for, the text in the peripheral file was displayed. However, on a triggering event, the central text file suddenly became the display list. This was done by simply changing the contents of the control word holding the beginning address of the display list. Thus, when the display processor completed a refresh cycle, it jumped to the other list and thus displayed the other text file. The delay, then, was always less than a refresh cycle period.

The display change was triggered when the eye crossed a certain boundary (character position) on a certain line, if the eye were travelling at least at a certain rate of speed. If the eye were travelling too slowly, the change was made the next time that speed was reached. Thus, the display change was determined by three parameters: CLINE, which contained the number of the critical line; BOUND, which contained the character position which served as the boundary; and THRSH3, which contained a distance threshold that the eye must have travelled during the last 60th of a second if the change were to take place. The change occurred if (1) the person was reading line CLINE; (2) there had previously been at least one fixation to the left of character position BOUND; (3) the eye was now to the right of character position BOUND; and (4) the change in the EMM signal value from the last eye position sample to the present one was at least the value THRSH3.

This version of EYETRACK used the same technique for identifying the line being read as was used in EYETRACK C; that is, the EMM signal for vertical movement was disregarded and a heuristic was used instead.

In the Boundary Experiment this version of EYETRACK was used to change the contents of a single word position in the text when the eye was at a certain location. Thus, the two text files were identical except for the contents of that one word position. Since there was no window to force the reader to comply with the restrictions of the eye tracking system, it was occasionally found that the reader violated these rules. The result was that the display change took place when the person was reading the wrong line. Essentially two types of rule violations occurred: sometimes the reader made a regression, either returning to a previous line and rereading it or making a long regression on the same line, and sometimes the reader failed to fixate the spot on the CRT until the new text page was brought in. When the reader returned to an earlier line the system did not recognize this, so it continued behaving as if he were reading the same line. This resulted in a data pattern showing the reader as having read one more line of text than existed in the display. When the reader made a long regression, causing the computer to assume that he had gone on to the next line when in fact he was simply rereading part of the same line, again the data pattern showed him reading an extra line of text.

The place where the error occurred was often identifiable in this case, since the reader often had not reached the end of a line when he regressed. Thus, it was possible to determine whether this error had occurred prior to or after the display change had taken place; that is, to determine whether the display change had occurred at the proper place in his reading. Finally, in order to keep readers from anticipating the onset of a new page of text and to jump to the first line before it was displayed and the computer had initiated the collection of data, subjects were instructed to look at the spot in the upper right-hand corner of the display, press the lever for a new page, and count to twenty-five before beginning to read. Subjects occasionally failed to follow these instructions and anticipated the onset of a new page of text by jumping to the first line before the new line appeared, or immediately after it appeared and before data collection began. When this happened, the data showed the person reading the right number of lines, but the first line read was labelled line -3 rather than line 0 in the data (lines were triple-spaced, so were numbered in increments of 3). Thus, the display change took place one line too late, but the occurrence of this event was clear from the data. From this discussion of types of errors, it is clear that each of the errors was clearly marked in the data, thus making it possible for erroneous data to be deleted from further consideration.

The location of the display change was also clearly marked in the data: a pair of data words set to all zeroes was placed between the words containing data for the fixation preceding and that following the change.

Thus, the D version of EYETRACK was very similar to the C version, collecting data, and using a heuristic to identify the line being read. The difference was in the display changes made; the D version produced a single display change during a page, whereas the C version produced a change in the display with every fixation. The type of display changed produced was also different, version C producing a window by integrating characters from the two files, and version D making a change in a single word location.

For all versions of EYETRACK, typing a D on the teletype caused control to return to the Top Level.

RUN. The RUN program was a routine which called other programs in a sequence needed to conduct an experiment. It first allowed the experimenter to specify the information needed to conduct an experimental session: the text files and data files to be used, the experimental conditions for each page of text (with the A, B, or C versions of EYETRACK this included the values for HITE, WIDTH, XOFSET and YOFSET for each page, and with the D version, the values for CLINE and BOUND for each page), and which version of EYETRACK to use. It then called CALIB, and when calibration was complete it called the specified version of EYETRACK, and opened and closed the required files at appropriate times. Thus, an experimental trial could be run, including calibration and the reading of a series of pages of text, without any interruption from the experimenter. The pages read could occur in different experimental conditions (different size windows or different boundary locations) during such a single trial.

PLOT. The PLOT program sampled either the vertical or horizontal eye position information every sixtieth of a second and simply stored the data until a certain number of samples had been taken. It then plotted the data on a Calcomp plotter, marking the onset and offset of each fixation with a slash. Thus, with this routine it was possible to set the THRSH value in EYETRACK, the parameter used to determine when saccades began and ended, to different values and see the effect this had on the accuracy of the system for identifying these events. It also yielded a picture of the eye movement characteristics of a particular subject.

VIEW. The VIEW program required the specification of peripheral and central text files and a data file, together with values for HITE, WIDTH, XOFSET and YOFSET. It then took the first 2-word data block and constructed the display on the CRT of exactly what was present for the person reading under the EYETRACK B or C routine on that particular fixation. At the bottom of the CRT it indicated numerically the line and character position of that fixation, the duration of the fixation, and the length of the saccade that had arrived at that fixation. The observer could then step through the data by pressing the space bar on the teletype. Typing a backarrow caused it to step backwards. Numerical arguments could also be entered: typing a number prior to pressing the space bar or backarrow key caused the program to create the display seen by the subject that many fixations after or before the present fixation. In addition, typing a C caused the program to advance the display from fixation to fixation automatically. When in that mode, typing a number followed by a carriage return set a new rate for stepping through the data and changing the display. Typing another C caused the program to go out of automatic advance mode. Finally, typing an N placed a cursor at the location of the next fixation, but otherwise did not change the display. Thus it was possible to observe, when the display was in a particular state, where the eye was sent for the next fixation. New pages of text could be obtained by pressing a lever. Typing a D returned control to the Top Level.

Other Routines Callable from Top Level. LOAD was a routine which opened a file, either text or data. It called for teletype specification of a device name and file name, and then for an argument to indicate whether this was to be specified as a central text file, peripheral text file, or a data file. TRANSLATE caused a text file specified in LOAD to be read in, to be translated from ASCII to the code used by the DEC Model 340 Display system, and to be stored in the appropriate core memory area. COMPLEMENT changed the size of the characters displayed. The Model 340 Display allows 4 character sizes. Our programs only allowed the two middle sizes to be used. ACTIVATE caused the text in the peripheral text file to be displayed. OPEN caused the opening of a channel for the output of data. If a channel were not opened, the EYETRACK programs would function properly, but no data would be saved. CLOSE closed the data output channel. RELEASE caused all devices captured by the EYETRACK program to be released and thus to become available to other users.

It should be noted that most of these routines were called by the programs described earlier, as well as being callable individually from the Top Level.

Characteristics of the Eye-movement Controlled Display System

Two questions are of paramount importance in considering the adequacy of the system described above. First is the question of accuracy of identifying eye position, and second is the question of time lag.

As indicated earlier, the accuracy of vertical eye movement information was quite poor. It appeared to be necessary to use quintuple spacing of the text, at least, to be able to reliably identify the line the person was looking at. For this reason the attempt to use this information from the EMM was abandoned, and the heuristic described earlier was employed instead.

Accuracy on the horizontal plane was a function of the experimenter's experience in adjusting the equipment on the reader, and of the range over which the eye was to be tracked. In general, crosstalk was quite severe when the reader viewed the lower third of the CRT displayable area. Therefore, all display was kept in the upper half of the displayable area.

An attempt was made to assess the accuracy of the system by having different people look at a display of a series of points, instructing them to fixate the points one-by-one, and then examining the computer's estimates of where they were looking. This sort of assessment is inadequate because it is not at all certain that when the person attempts to fixate the same point at different times that he in fact returns his eye to the same position. Thus, lack of reliability may be due either to characteristics of the eye positioning system, or to our equipment and programs for monitoring eye position. Practically all computer-indicated locations were no more than one or two character positions from the reportedly fixated location.

During the first experiment reported, accuracy was not quite this great, due to our inexperience in using the eye-tracking equipment, and in conducting this type of research. There was evidence at times during that experiment that head position had shifted slightly during the reading of a passage; we later found ways of making the subject more comfortable and fixing the head more rigidly to reduce this problem.

Drift in the eyetracking equipment did not seem to be a problem, since subjects went through the calibration routine prior to reading each block of text, and these blocks were relatively short, only about 500 words for the first four experiments, and slightly longer for the last.

The problem of lag in the system is also difficult to assess. The question is, how long after the eye actually began or ended a saccade was this event detected by the computer? The delay was much longer than we had realized at the time we were conducting the research. We have attempted to more thoroughly investigate the characteristics of the eyetracking equipment since completion of the research, and have found a considerable delay which raises some questions about the interpretation of the data collected. This delay was the result of two things: first, a filter in the Biometrics Eye Movement Monitor, and second, using a sampling rate of 1/60th of a second.

The Biometrics equipment is provided with a filter which was left engaged during our research and which introduces a considerable delay in the signal. Without the filter, the stimulating of one of the photo-diodes with a fast-rising infrared signal causes the analogue output from the equipment to begin rising almost immediately, reaching maximum level in 4 or 5 milliseconds. The time required seems to vary on successive trials, though the reason for this is not apparent. When the filter is engaged, the same stimulus still causes the output to begin rising almost immediately, but the maximum level is not attained for 25 milliseconds or more. Thus, there was probably a substantial delay between the time the eye began to move and the time that the EMM signal changed sufficiently to meet the computer's criterion for the initiation of an eye movement. Just how long this delay was, of course, is not known now.

Sampling the eye position only every 16 milliseconds also introduces a delay into the system. It was quite possible for the eye to begin moving during an interval between samples, but not to have moved sufficiently to be detected by the computer. Thus, another 16 milliseconds would elapse before the computer detected the eye as moving. Thus, the detection may not have occurred for 18 msec. or more after the eye actually began moving, even if there were no delay in the signal introduced by the eyetracking equipment itself. Since a saccade in reading requires about 22 msec. (Alpern, 1971), this amounts to an intolerable lag. On the other hand, it should be noted that if the eye movement began at the right time prior to a sample it would be detected within just a few milliseconds.

The combination of a slow-responding signal and a relatively slow sampling rate resulted in considerable lag, the amount of which is not known. However, an attempt was made to estimate grossly the amount of lag, from saccade velocity characteristics, characteristics of the rise and drop in EMM output to square-wave input signals, and the knowledge of the threshold used by the computer in determining onset and offset of saccades (if the eye moved more than about 1/2 character position in 1/60th of a second, it was said to be moving; if less it was said to be stopped). This estimate suggested that the computer might identify the beginning of an eye movement from about 8 to 23 msec. after it began, for a 25 msec. saccade. Lag times for identifying the initiation of a fixation were even slower, probably in the range from about 30 to 45 msec. after the fixation actually began, following a 25 msec. saccade. Thus, while we thought that we were identifying eye movement events within just a few milliseconds, we were actually not identifying the initiating of a saccade until it was well underway or almost complete, and were not identifying the onset of a fixation until the eye had been stopped for a considerable period of time.

Since the system was substantially faster at identifying the onset of a saccade than the onset of a fixation, the measurement of time required by saccadic movements was probably inflated, and the measurement of time spent in fixations was probably underestimated.

In the final experiment to be reported, referred to as the boundary study, an attempt was made to change the display while the eye was moving. To try to do this, it was required that the eye had achieved a minimum velocity before the change could take place. In view of the preceding comments it is quite clear that much of the time the change must have occurred after the saccade was in fact finished, rather than during the eye movement as we believed was occurring at the time. However, visual suppression following a saccade and visual masking phenomena probably minimized the effects of these delays on reading behavior.

In addition to the filter just described, an additional filter was attached to the output of the eye movement monitor. This was an RC filter network containing a 10K Ohm resister and a .033 MFD capacitor on each channel. This network had the effect of filtering out high frequency signal variations, and introduced about 1/3 msec. delay, as well.

The response time of the system could be greatly increased, of course, by disabling the Biometrics filter. It is not known what changes in the software would then be required to reliably detect the onset of saccades and fixations.

Computer Programs Developed for Processing the Data

Two programs were developed for representing and summarizing the data: EDATA, which converted the raw data to ASCII characters and produced summary statistics for the data from reading each page of text, and MARK DATA, a set of programs for printing out text with the location and duration of each fixation marked on it, and for producing frequency distributions for certain aspects of the data.

EDATA. The EDATA program was prepared in the PDP-10 assembly language. It first converted the raw data into ASCII character form. As indicated earlier, for each fixation there was a two-word data block indicating the location of the present fixation (line number and character position), the duration of this fixation, and the duration of the previous saccade. EDATA created one line of ASCII characters for each block of data, containing the line number and character position of that fixation, the number of that fixation (counting from the beginning of the passage), the duration of the fixation, the time required for the saccade, the length of the saccade in character positions, and a number indicating type of movement: forward movement, regressive movement, forward in a regression (that is, following a regression, a forward movement that does not yet bring the eye to the point from which the regression occurred) and return sweep. EDATA also compiled a large number of summary statistics for each page read. These included: the number of fixations per hundred characters, total time spent reading the page and time per hundred characters, amount of time spent in eye movements and the time spent in fixations, number of regressive movements per 100 characters, and the first, second and third quartiles for the distribution of fixation durations, saccade lengths, and time required for saccades. These quartile values were also compiled for each of the four types of eye movements separately.

EDATA permitted one additional option. A problem that was occasionally encountered was that there appeared to be more fixations identified by the computer than actually occurred. Under certain circumstances, either due to the adjustment of the equipment or perhaps due to subjects' eye characteristics, there would be a number of short fixations on the same or adjacent character positions. Thus it appeared that the system was too sensitive to eye movement on these occasions, and identified slight visual drifts as saccades. Therefore, it was decided that two successive fixations on the same or adjacent character positions would be defined as a single fixation. EDATA could be instructed to make this change in the data as it produced the ASCII representation and summary statistics. Most of the data was in fact modified in this way, in order to maintain consistency. If this modification seemed desirable for part of a subject's data, all of his data was modified. This was done in order to keep from biasing the data for different conditions, since all subjects were tested in all conditions in each experiment.

MARK DATA. The MARK DATA routines were prepared in the MIT Artificial Intelligence Laboratory version of TECO, an editing language. They took as input a file of text which a subject had read, and a file of data in ASCII form which had been collected as the subject read that text. They then merged these two into a file which could be printed out, which showed the text read, marked with the location of each fixation and the duration of that fixation, and then listed the ASCII data below, identifying each fixation by number and showing the fixation duration, time required for the saccade, the length of the saccade, and the mode of that fixation and/or saccade (forward fixation, regression, forward in a regression, or a return sweep). This made it possible to examine the eye movement data in detail, in context of the text being read. An example of this output is shown in Figures 2 and 3.

```
    INTELLIGENCE TESTS IN THE FORM GENERALLY USED TODAY HAVE DEVELOPED
    1            2          3      4            5       6   7
    31           16         11     14           17      17  4
FROM THE WORK OF ALFRED BINET. A FRENCH PHYSICIAN AND PSYCHOLOGIST.  BINET
  -9        0          1    2       3         4          5    6   7
  13        13         27   28      15        12         12   13  7
WAS ASSISTED BY ANOTHER FRENCH PHYSICIAN AND PSYCHOLOGIST, THEODORE SIMON.
   8       9      0       1         2            3            4   5
   18      11     14      12        12           13           15  26
AFTER MUCH CAREFUL STUDY AND RESEARCH THESE MEN PUBLISHED THEIR FIRST TEST
  6     7     8         9         0          1        2          3    4   5
  31    14    11        11        23         10       14         11   8   10
OF INTELLIGENCE IN 1905.  THIS TEST CONSISTED OF THIRTY TASKS TO BE PER-
   6    7               8           9        0             1      2      3
   15   12              43          12       13            13     14     30
FORMED BY CHILDREN.  IT MUST BE UNDERSTOOD THAT THESE TASKS WERE NOT THE
  4               5           6      7             8           9     0
  15              14          13     12            13          15    10
KINDS OF TASKS THAT THE CHILDREN WERE REQUIRED TO LEARN IN SCHOOL.  ON
          1     2         3    4              5            7 6
          18    17        6    11             13           1112
```

Figure 2 - Text marked with fixation positions and durations. This is an example of output from the MARK DATA program. The top number of each pair indicates fixation sequence, Modulo 9, and is the last digit of the number of that fixation, counting from the beginning of the passage. The bottom number is the duration in 60ths of a second.

Y	X	#	MT	FT	SL	M
0	5	1	16	31	-61	3
0	18	2	4	16	13	0
0	28	3	4	11	10	0
0	35	4	3	14	7	0
0	47	5	3	17	12	0
0	55	6	3	17	8	0
0	59	7	1	4	4	0
2	-1	8	13	13	-60	3
2	3	9	2	7	4	0
2	12	10	3	13	9	0
2	22	11	3	27	10	0
2	27	12	3	28	5	0
2	35	13	4	15	8	0
2	44	14	3	12	9	0
2	55	15	5	12	11	0
2	60	16	2	13	5	0
2	64	17	2	7	4	0
4	3	18	17	18	-61	3
4	10	19	4	11	7	0
4	19	20	4	14	9	0
4	26	21	3	12	7	0
4	36	22	4	12	10	0
4	49	23	4	13	13	0
6	46	31	4	10	10	0
6	54	32	3	14	8	0
6	63	33	4	11	9	0
6	67	34	1	8	4	0
6	70	35	1	10	3	0
8	3	36	13	15	-67	3
8	8	37	2	12	5	0
8	22	38	5	43	14	0
8	34	39	5	12	12	0
8	42	40	3	13	8	0
8	55	41	4	13	13	0
8	62	42	3	14	7	0
8	69	43	3	30	7	0
10	2	44	13	15	-67	3
10	17	45	5	14	15	0
10	28	46	4	13	11	0
10	37	47	3	12	9	0
10	51	48	4	13	14	0
10	62	49	4	15	11	0
10	68	50	3	10	6	0
12	10	51	12	18	-58	3
12	16	52	3	17	6	0
12	26	53	4	6	10	0

Figure 3 - An abbreviated listing of eye movement data provided by the MARK DATA program for the page shown in Figure 2. Each row of seven numbers provides data on a particular fixation. Key to the columns is as follows: Y - line number of the fixation location; X - character position of the fixation location; # - number of the fixation counting from the beginning of the passage; MT - time required for the last saccade; FT - duration of the fixation; SL - length of the last saccade; M - type of fixation (forward, regression, forward in regression, return sweep). Time is measured in 60th of a second, distance in number of character positions.

The MARK DATA routines could also be asked to prepare a complete frequency distribution for fixation durations, saccade durations, or saccade lengths for each page of text read.

Computer Program to Prepare Materials for the Experiments

An additional program was prepared in the TECO language to assist in the preparation of text for the window experiments. The program had a number of letter-substitution tables. It accepted a page of normal text as input, and when a single-letter command was typed it output a modified version of the text, with each character replaced by the appropriate character as specified in the letter-substitution table specified by the command. The tables used were the following: replace every character except carriage return and line feed with an x; replace every letter or number with an x, maintaining case; replace every letter and number with another selected to be visually confuseable with it; replace letters and numbers with specified visually confuseable characters and replace punctuation marks and spaces with specified letters; replace every letter and number with another selected to be very different from it in visual characteristics; and replace every letter and number with a specified visually different character and replace punctuation and spaces with designated characters. The text files created with these routines were used as peripheral text files in the window experiments.

CHAPTER 4

WINDOW EXPERIMENT I: A PILOT STUDY

Once the computer programs for conducting the research had been developed and an attempt made to assess their accuracy and their operating characteristics, an initial pilot study of the window type was conducted. The primary purpose of this study was to learn whether subjects could successfully read text under these unusual conditions: that is, when normal text was displayed in the central visual region, and a distorted text pattern in the peripheral visual areas. It seemed quite possible that the massive display changes occurring on every fixation would be so disrupting to the visual system that normal reading would be impossible. If it were possible for the subjects to read successfully, then we were interested in obtaining general data on the effects which the two variables manipulated had on reading. These variables were the size of the region within which normal text was displayed (referred to as window size) and the type of modification made in the text pattern outside the window region (referred to as the peripheral text pattern). In this study, the window always included text on a single line, the one being fixated, and was centered with respect to the fixation point.

Method

Subjects. Eight high school students from the Boston area were paid to participate in the study. All were juniors or seniors in college preparatory programs and were above average readers; all but one were specifically identified as being among the top ten percent of their class on reading tests administered by their schools.

Materials. Two sets of passages were prepared for the subjects, one for practice and one for the experiment itself. The practice passages and their tests were taken from the Carver-Darby Chunked Reading Test (Carver and Darby, 1971). In addition, twelve 450-word passages were extracted from high school history, chemistry, and biology texts for use in the experiment. Each passage was divided into four pages, and eight questions requiring short written answers were prepared for each passage, two testing information from each page of the passage.

Four peripheral text versions of each passage were prepared by replacing characters in the original text with other characters. These versions were: Confusable-spaces (CS), in which each letter was replaced by a letter visually similar with it, as shown by visual confusion data (Hodge, 1962; Bouma, 1971), and with spaces and punctuation left intact; nonconfusable-spaces (NCS), in which each letter was replaced by a character visually different from it, and again with spaces and punctuation remaining; X-spaces (XS), in which each letter was replaced by an x, with case maintained and with spaces and punctuation intact; and X-filled (XF) in which each character, space and punctuation mark was replaced by an x. Thus, the three S versions maintained word length patterns, punctuation and capitalization characteristics of the original text, whereas these were destroyed in the XF version. The CS version maintained word shape characteristics, since ascending letters were always replaced by ascenders, and descenders by descenders, etc., as well as maintaining certain featural characteristics of the letters themselves. The NCS version presented incorrect word shape information, and the XS version destroyed all aspects of word shape except for the presence of capitalization.

Design. The experiment consisted of a 4 by 6 design, with the four peripheral text versions just described, and with six window sizes, 9, 13, 17, 25, 45 and 140 character positions wide. A window of size 13 provided normal text at the character position which the computer identified as being directly fixated, and the 6 character positions to right and left of that position. Thus the window included characters only on the line being read, and was centered with respect to the character position in central vision. When the subject fixated near the end of a line, and the window area extended beyond the text, the actual number of characters of normal text displayed was less than the window size. A window size of 140 was used in one condition to ensure that no matter where on the line the subject fixated, the entire line of text would consist of normal text from the central text file. Thus, in this condition no display change occurred except when the subject made a return sweep to go to the next line.

The two variables just described were combined factorially to produce 24 experimental conditions. Each subject read 12 passages of 4 pages each, or a total of 48 pages of text, and thus read two pages under each of the experimental conditions. The conditions were balanced as well as possible over passages and over page sequence within passages, for the eight subjects used in the study.

Procedure. Subjects came to the laboratory individually and each participated in three sessions of 1 1/2 to 2 hours in length. During the first session a dental impression was made on a bite bar, the subject was instructed in the nature of the research, and he was given practice reading with various window sizes and peripheral text conditions. After the bite bar had been prepared, the glasses on which the eye position sensors were mounted were placed on the subject and the sensors were adjusted to minimize non-linearity and crosstalk in the signal. This was done by having the subject repeatedly fixate points in a nine-point calibration pattern, with three rows of three points each, while the sensors were adjusted. Following this adjustment, the subject was allowed to rest, and the nature of the research was explained to him. For this study the EYETRACK C program was used, which employs a heuristic for identifying the line on which the person is reading. It assumes that the reader begins on the first line, and that he continues to read that line until a leftward movement or series of movements is made which totals 45 character positions in length. The nature of this heuristic was explained to the subject, together with the restrictions this placed on his reading behavior: he must not make long regressions, he is not able to return to a line previously read, and he must begin each page by fixating a dot in the upper right hand corner of the screen before starting to read. Then the subject read four or five practice passages to see how the system worked, being tested after each. He was encouraged to try violating the rules of the system explained to him to see the effects of doing so. Prior to reading each passage, the subject went through the calibration routine, fixating a series of 25 points on the display, and pressing a lever as he looked directly at each point. Pressing the lever one additional time brought onto the screen the first page of the peripheral text version of the passage to be read. When the subject moved his eyes to fixate the beginning of the first line, a window of normal text appeared at his area of fixation, and each time he changed his eye position, the appropriate window appeared at his new fixation point. Thus, he was able to read the text, though in some conditions this was made more difficult due to the narrow window and hence to the narrow region from which full text information could be obtained during a fixation. Each additional press of the lever called another page of text onto the screen. When finished reading the last page of a passage, the subject removed himself from the bite bar and took the test on that passage.

During the second session the experiment actually began. After adjusting the eye position sensors, the subject was allowed to read two passages for warm-up. Then he read six of the twelve passages used in the experiment, removing himself from the bite bar and being tested after each. Prior to reading each passage, he went through the calibration routine once again to ensure that any change in his head position or the position of the sensors was adequately accounted for by the eyetracking routines. While the subject took each test, the experimenter typed into the computer the conditions under which the four pages of the next passage were to be read. He then scored the subject's test and gave him a report of his test score, since the subject was paid partly on the basis of his test performance. As the subject read each passage, the experimenter carefully watched the display on an auxiliary CRT and noted any irregularities which occurred: for instance, it was often quite noticeable when the subject made a pattern of eye movements which caused the window to advance to the next line too soon. These notes and an examination of the data patterns served at a later time for eliminating eye movement data from analysis for those regions of the text where such irregularities were noted.

The third session proceeded in the same manner as the second, with the subjects reading the second set of six passages.

Results

Summary statistics were obtained for certain aspects of the eye behavior data for each page read by each subject, including reading time per 100 characters, median saccade length, and median fixation duration. These data will now be summarized.

Figure 4 shows the effect of window size and peripheral text pattern on reading time. Reducing the size of the window slowed reading considerably. The peripheral text pattern seemed to have an effect primarily at the smallest window sizes, and the amount of that effect was much less than the effect of window size.

The saccade length data were analyzed with a three-way analysis of variance, with the factors being subjects (8), window sizes (6), and peripheral text patterns (4). The data entered into the analysis were medians for each page read; thus, each subject contributed two medians for each condition in the experiment. Two significant main effects were found for these data, for window size ($F = 42.71$, $p < .001$, 5 & 35 df) and for subjects ($F = 49.79$, $p < .001$, 7 & 192 df). In addition, there were three significant interactions, that between window size and peripheral text pattern ($F = 2.153$, $p < .05$, 15 & 105 df), that between window size and subjects ($F = 2.60$, $p < .01$, 35 & 192 df) and that between peripheral text pattern and subjects ($F = 1.83$, $p < .05$, 21 & 192 df). The main effect for window size and the Window Size x Peripheral Text Pattern Interaction can be seen in Figure 5. There was a general tendency for smaller window sizes to reduce the lengths of the saccades. The interaction between these variables is complex and will not be discussed further since it was explored more completely in the experiment to be described in the next chapter.

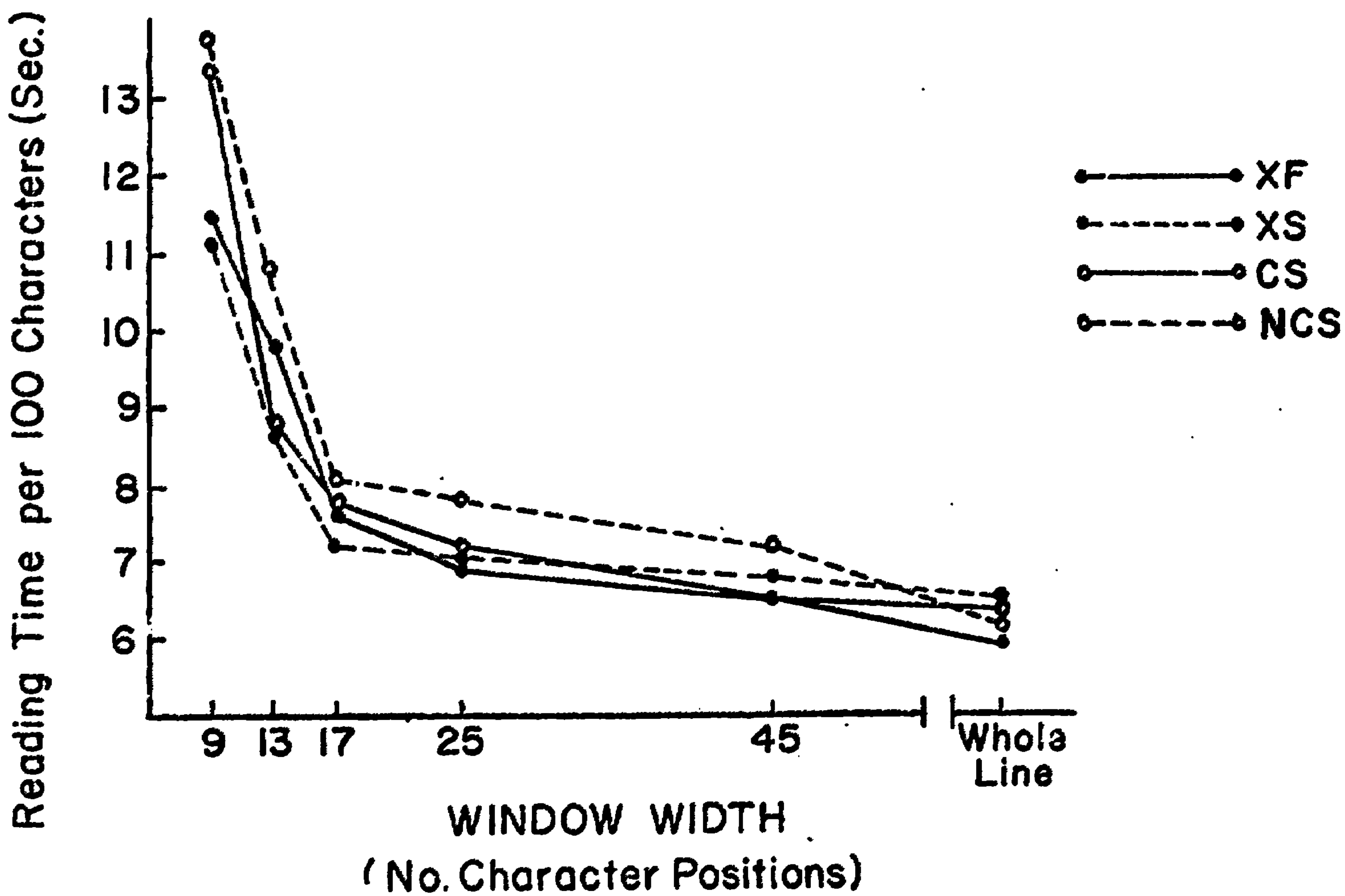

Figure 4 - Window Experiment 1: Effect of window size and peripheral text pattern on reading time per 100 characters.

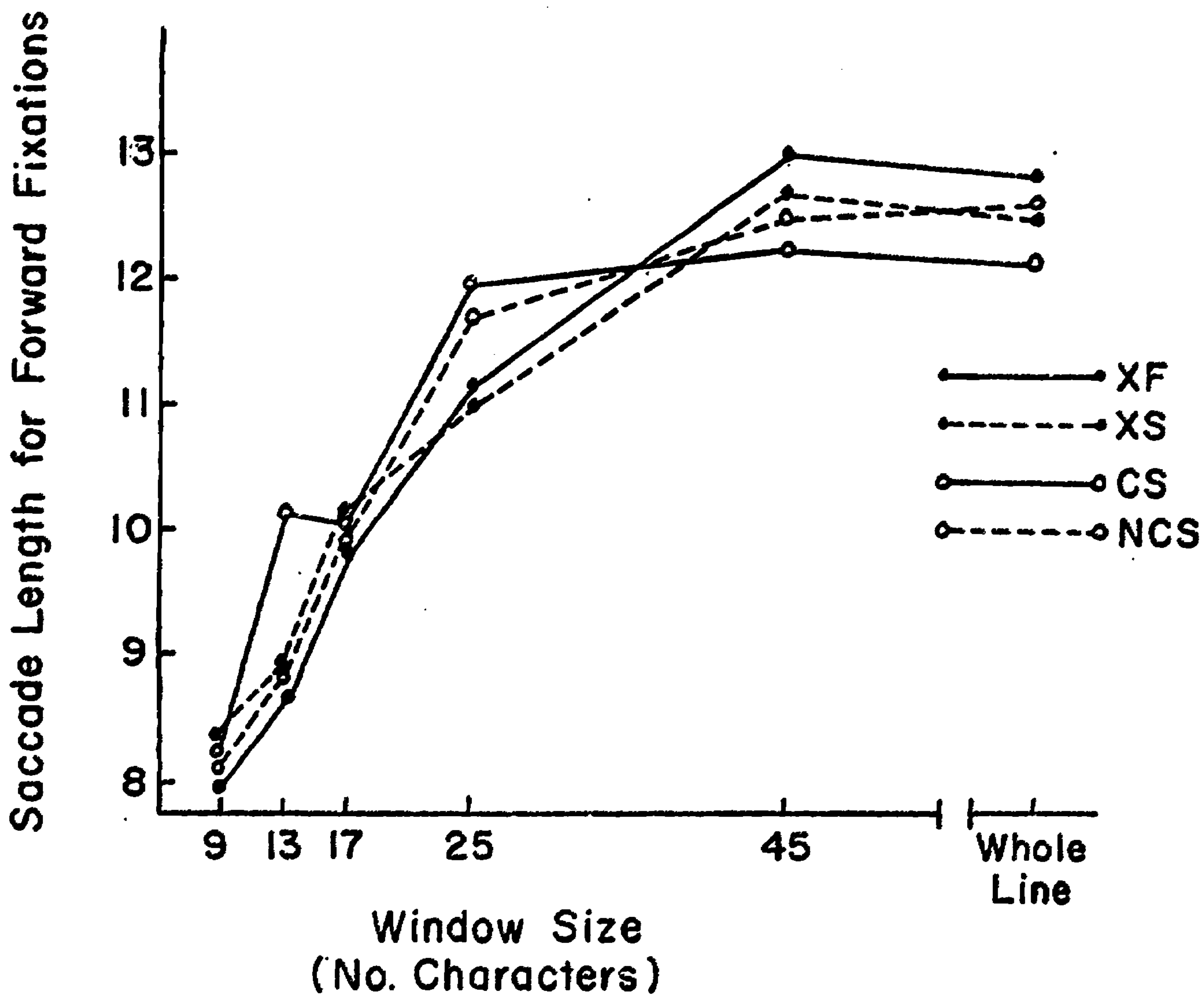

Figure 5 - Window Experiment I: Effect of window size and peripheral text pattern on median saccade length.

The Window Size X Subject Interaction was examined further and appeared to arise largely from the behavior of two subjects whose reaction to the reading situation seemed to be quite different from that of other subjects. Further examination of these two subjects found that one (who had volunteered for the research and was not obtained through the same channels as the other subjects) tended to have reading difficulties and was much less skilled in his reading than the other subjects were. The other deviant subject was a good reader, but it was discovered that she often had trouble fixating a target. She reported that her eyes often did not both focus on the same location and that she had sought medical assistance for this visual problem. These subjects were not asked to participate in later studies.

The fixation duration data were treated in the same way as the saccade length data just described, with each subject contributing two medians for each of the experimental conditions to a three-way analysis of variance. Two main effects were found to be significant, those for window size ($F = 76.19$, $p < .001$, 5 & 35 df) and for subjects ($F = 37.33$, $p < .001$, 7 & 192 df). No interactions were significant. Figure 6 shows that as window size was reduced, the median fixation durations increased.

Figure 7 shows the number of regressions made in reading the passages. There tended to be more regressions when the subjects were reading with the smallest window size.

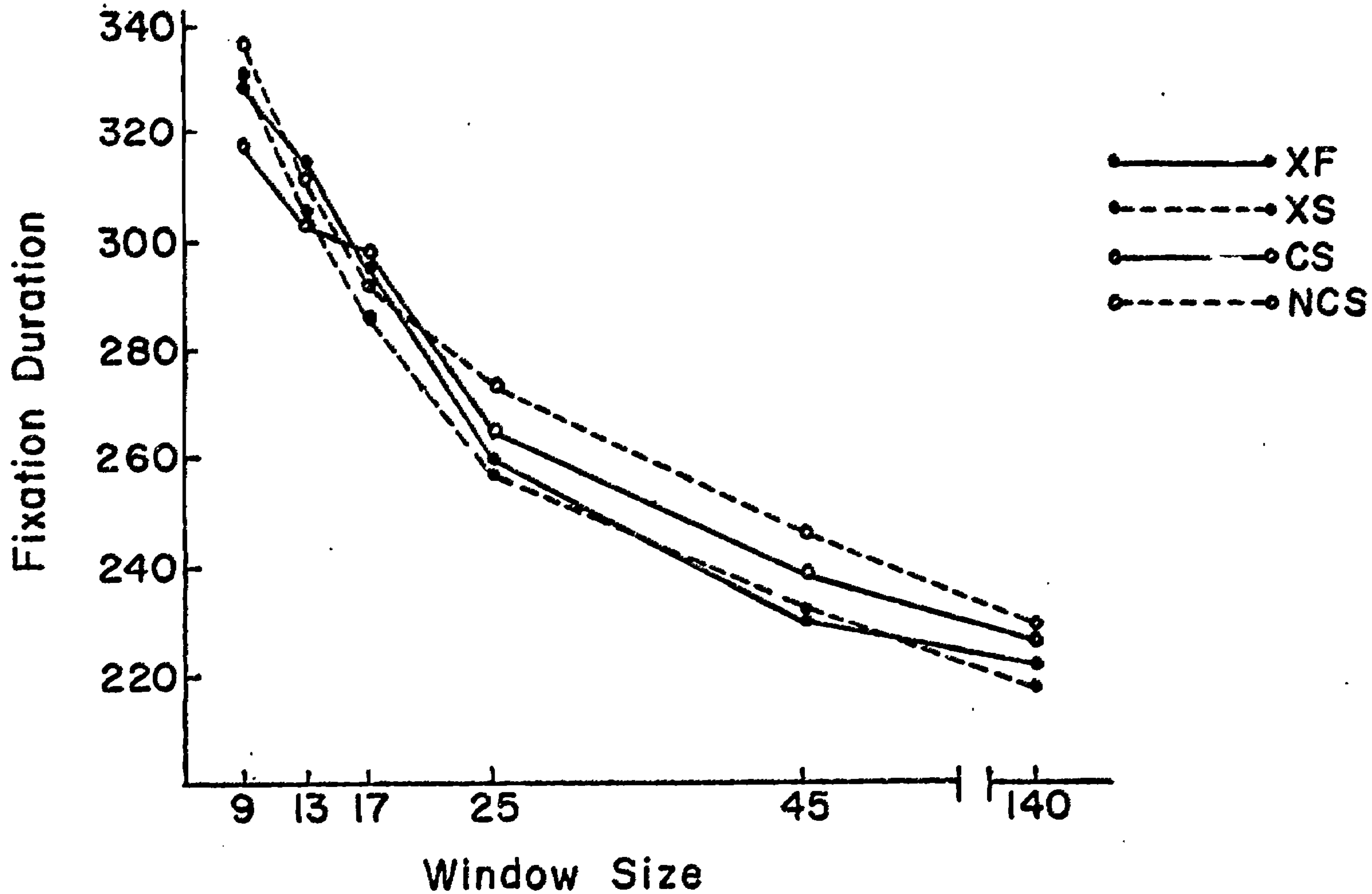

Figure 6 - Window Experiment 1: Effect of window size and peripheral text pattern on median fixation duration.

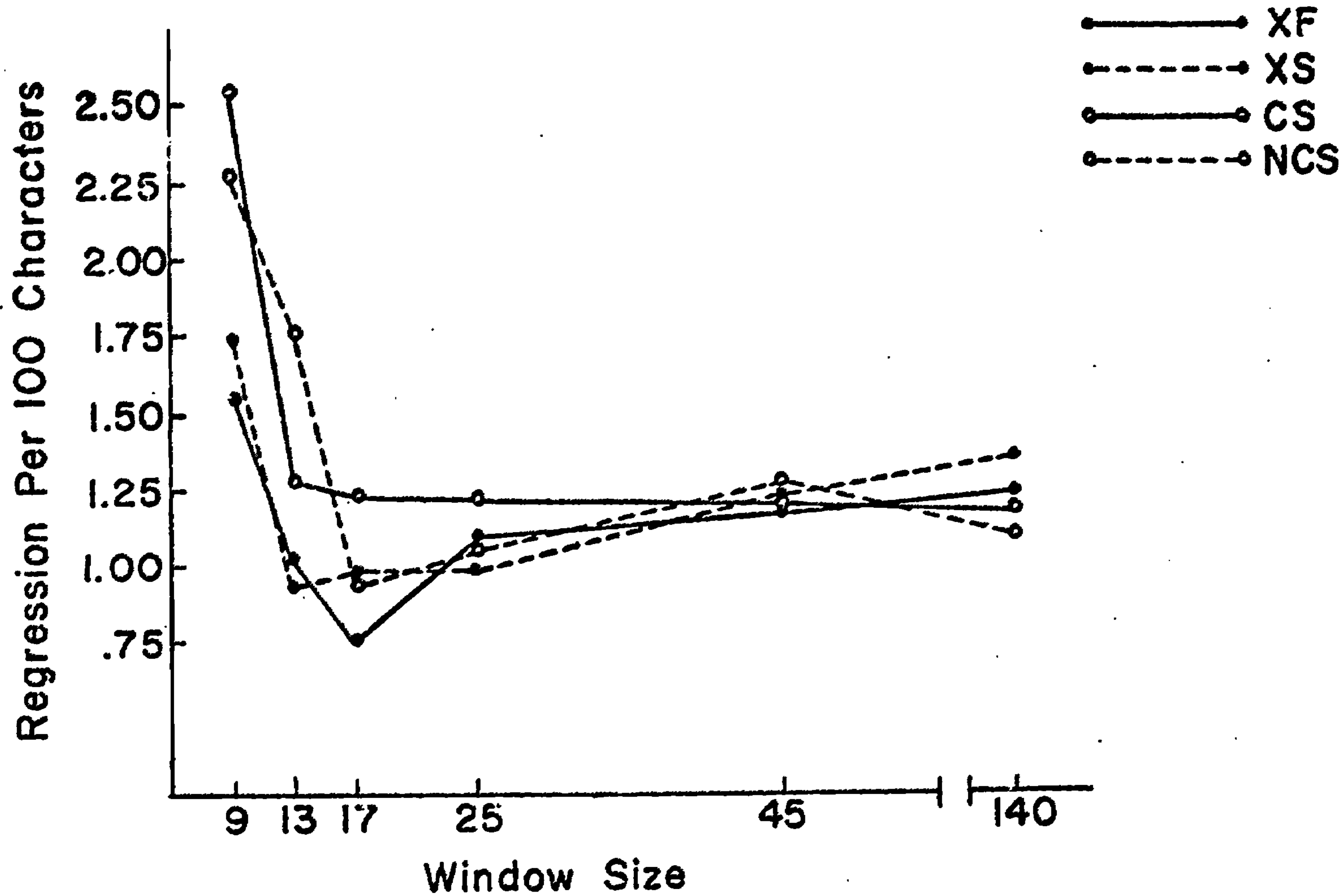

Figure 7 - Window Experiment I: Effect of window size and peripheral text pattern on the number of regressions.

An analysis of variance carried out on the number of questions answered correctly which tested information from pages read under the various conditions found no significant main effects or interactions. Percent of questions answered correctly ranged from 55% to 65% for the different conditions, with an overall mean of 58%.

Discussion

From the data and reported experiences of the subjects in this study it was concluded that subjects were able to read quite naturally in the type of situation which was provided. It was clear that reducing the size of the window caused them to slow their reading, and they also reported experiencing some frustration in attempting to read with the smallest window sizes, as if they were having to push against some limitation or force which was holding back their reading speed. Other than this, however, they reported that when they were attempting to read the passages for meaning the display changes occurring did not seem to intrude or keep them from their task. They were aware, if they desired to be, of the window boundaries of the smaller window sizes, and had the impression of changes taking place in their peripheral vision if they paid attention to them. However, these went quite unnoticed when the subject concentrated on reading to understand the passage.

Reducing the window size affected all three eye behavior variables used: fixation durations increased, saccades shortened, and number of regressions increased, though this latter increase only occurred at the smallest window size. Type of peripheral text pattern was only found to affect the length of saccades, interacting with window size, and had no clear effect on the other measures. This interaction seemed to occur primarily at the smallest window sizes, which suggested that later research should use more smaller window sizes in attempting to determine just how far into the periphery different types of peripheral text patterns have an effect on reading behavior.

Thus, it was concluded that the basic technique being used was capable of producing reading behavior changes which may be useful in determining how far into the periphery specific types of visual information are being acquired during a fixation by the reader, and that an additional study should be conducted which involved more systematic contrasts between types of peripheral text patterns, and which had a number of window sizes in the smaller region.

One finding of particular interest in this study was that while window size had a significant effect on reading speed, it had no significant effect on test performance. When a person reads under conditions in which he can see only nine character positions at a time he has certainly been reduced to being a word-by-word reader. That is, it is seldom possible for him to identify more than one word at a time. Smith (1971) and others have suggested that one reason why poor readers fail to comprehend meaning as they read is because they are not capable of taking in larger chunks of information at once during a fixation; that is, they are obtaining only a word at a time. He claims that this causes the limited capacity information processing system to have to deal with more chunks of information, thus overloading the system and making it impossible for the reader to integrate the meaning of the text as he reads. It is of interest, then, that reducing a group of good readers to being word-by-word readers fails to have these devastating effects on their comprehension of the text. Though they read more slowly, they seemed able to comprehend and retain information from the passage just as well when reading with a very narrow window as when reading with a wide one. Thus, this finding seems to call into question the above described mechanism as being a primary basis for the low comprehension level of poor readers.

CHAPTER 5

WINDOW EXPERIMENT II: WIDTH OF THE PERCEPTUAL SPAN

Using the information gained from the pilot study described in the last chapter, an experiment was designed to investigate more completely the interaction between window size and peripheral text pattern. Additional peripheral text patterns were included in this experiment which allowed further exploration of the effects of word shape and word length patterns in peripheral vision. More window sizes were used, and these were concentrated around the area in which the pilot study indicated peripheral text pattern may have an effect. A more full analysis of the data was also carried out.

The primary purpose of this study was to determine just how far into the periphery two types of visual information were acquired by the subjects during fixations in reading. These types of information were word shape and word length patterns. The research design involved factorially combining a number of window sizes with several peripheral text patterns, and having each subject read two pages of text under each of the resulting conditions. The strategy was to compare the reading behavior at each window size for peripheral text patterns that did and did not contain a certain visual characteristic of the normal text (say word shape). If it made no difference whether or not that characteristic was contained in the text pattern outside the window at a particular window size, this suggested that the reader was able to acquire the visual information involved completely within the window area. If at another window size, having that characteristic in the peripheral text pattern facilitated reading in comparison with having it deleted, this suggested that the reader was picking up the visual information involved in a region outside the window.

The strategy for the research, then, was to compare the eye behavior indices for specific peripheral text pattern comparisons at each successively larger window size, to determine at what point there was a transition from the peripheral text pattern having an effect on reading, to its failing to have such an effect. The window sizes at which this transition took place would indicate the distance into the periphery that the visual characteristic being investigated was being acquired and used by the subjects in their reading.

Method

Subjects. Six of the subjects who participated in the pilot study served as subjects in this experiment as well. By this time, each had six hours of experience in the type of reading situation used in this experiment. They were paid for their performance, including a base rate plus a bonus based on their performance on the test questions.

Materials. Sixteen 500-word passages were selected from a high school psychology text. None of the subjects had taken a course in psychology. Each passage was divided into six approximately equal size pages, which were displayed one at a time, double-spaced, during the experiment.

Six algorithms were used to substitute letters for characters in the original text to produce peripheral text patterns. Four of these were the same as used in the pilot study: XS, XF, CS, and NCS. In addition two new versions were introduced: CF and NCF. In the X versions, each letter was replaced with an x. In the C versions each letter was replaced by a letter visually similar (confusable) with it. In the NC versions, each letter was replaced by a letter visually different (nonconfusable) from it. In addition, the S (spaces) form of each of these maintained spaces and punctuation, whereas, in the F (filled) form each space and punctuation mark was replaced by an appropriate letter, an x in the XF version and other letters in the CF and NCF versions. In addition, in the XF version all replacement was done using capital X's, thus eliminating capitalization characteristics.

As an example, Figure 8 shows a line of normal text and the corresponding line after having letters substituted to produce each of the peripheral text versions.

	Graphology means personality diagnosis from hand writing. This is a
XS	Xxxxxxxxxx xxxxx xxxxonality diagnosis xxxx xxxx xxxxxxx. Xxxx xx x
XF	XXXXXXXXXXXXXXXXXXXXonality diagnosisXXXXXXXXXXXXXXXXXXXXXXXXXXXX
CS	Cnojkaiazp wsorc jsnconality diagnosis tnaw kori mnlflrz. Ykle le o
CF	Cnojkaiaqpewsorcejsnconality diagnosisetnawekoriemnlflrqeeeYkleeleeo
NCS	Hbfxwysyvo tifdl xiblonality diagnosis abyt wfdn hbemedv. Awel el f
NCF	Hbfxwysyvoetifdlexiblonality diagnosiseabytewfdnehbemedveeeAweleelef

Note.-On each line a window of size 17 is shown, assuming the reader is fixating the letter d in diagnosis.

Fig. 8. Window Experiment II: An example of a line of text and the various peripheral text patterns derived from it.

Two multiple-choice test questions were prepared for each page of text, thus yielding 12 questions for each passage. These questions tested retention of information clearly stated in individual sentences in the passage. Each question had four alternatives from which the subject was to choose.

Design. Forty-eight display conditions were used in this study, produced by factorially combining eight window sizes with six peripheral text patterns. The six peripheral text patterns have already been described; window sizes used were 13, 17, 21, 25, 31, 37, 45 and 100 character positions. Thus, for the smaller windows each successively larger window size extended the window by two character positions at each end.

Each subject read all sixteen passages (96 pages), with two of the pages being read under each of the 48 presentation conditions. All subjects read the passages in the same order, but the condition order was unique for each subject. An attempt was made to balance presentation conditions over passage and page sequence as far as possible. Each presentation condition occurred once in the first eight passages, and again in the last eight, for each subject.

Procedure. The procedure used was similar to that in the pilot study, and used the EYETRACK C Program. Each subject participated in the study for two two-hour sessions, reading the first eight passages during the first session and the last eight during the second session. At the beginning of each session, after the equipment was adjusted, the subject had the opportunity to warm up by reading two or three passages from the pilot study under conditions of various window sizes and peripheral text patterns. Prior to reading each passage the subject went through the calibration task. In the experiment itself, after reading all six pages of a passage he came off the equipment and took the test for that passage. Prior to reading the next passage, the test was scored and he was informed of his score. In order to encourage the subjects to put their emphasis on reading the passage to understand it and remember its content, they were given one cent for each question correct on each test.

Results

The Data. For each page of text read by each subject, summary statistics were obtained for a number of aspects of eye movement behavior, in addition to scores on the retention test. Each fixation and movement in the eye behavior data was categorized either as a forward movement and fixation, a regressive movement and fixation, a forward movement and fixation in a regression (if a regression had previously been made and this forward movement failed to bring the eye back to the point from which the regression was originally made), or as a return sweep. On the movement or series of movements which advanced the eye to the next line, all movements were categorized as return sweep movements, and fixations bounded on both sides by return sweep movements were identified as return sweep fixations. The fixation occurring at the end of a return sweep, which was then followed by a forward movement, was identified as a forward fixation.

Three types of eye movement data were analyzed. The first was time data. The reading time per hundred characters was computed for the page, and then this was broken down in two ways. First, it was broken into time spent in movement (Movement Time) vs. time spent in fixations (Fixation Time). Time spent in forward movements and in forward fixations was also obtained. Second, time was broken down by the categories of movements and fixations, yielding total time per 100 characters for forward movements and fixations, regressions, forward movements and fixations in regressions, and return sweeps.

The second type of data consisted of simple counts of the number of fixations and movements per hundred characters, both total for the entire page, and broken down into forward, regression, forward in regression and return sweep, in order to have the number of each of these types of movements and saccades which occurred.

The third type of data was measures of saccade lengths, saccade durations and fixation durations. Saccade lengths were measured in number of character positions. Both saccade and fixation durations were measured in 60ths of a second. As indicated in Chapter 2, characteristics of the equipment and sampling procedures used tended to inflate movement durations and underestimate fixation durations by a small amount. First, second and third quartiles were obtained from the distributions of all fixation durations and forward fixation durations for each page. Second quartiles (medians) were obtained for the distributions of fixation durations for regressions, forward movements in regressions and return sweeps. The same statistics were obtained for the distributions of saccade lengths and saccade durations, except that no statistics were included for distributions of all saccade lengths and durations. Thus, there were 34 dependent variables for which one score was obtained from each passage read. These variables are listed in Table 1.

TABLE 1

WINDOW EXPERIMENT II: A LIST OF DEPENDENT VARIABLES

Time Data:

- *Total time/100 characters
- Fixation time/100 characters
- Movement time/100 characters
- Forward fixation time/100 characters (Tim-ForFix)
- Forward movement time/100 characters
- Time in forward movements and fixations/100 characters (Tim-ForTot)
- Time in regressive movements and fixations/100 characters
- Time in forward in regression movements and fixations/100 characters
- Time in return sweep movements and fixations/100 characters

Frequency Data:

- *Number of fixations/100 characters (Num-TotFix)
- *Number of forward fixations/100 characters (Num-ForFix)
- *Number of regressive fixations/100 characters (Num-RegFix)
- Number of forward in regression fixations/100 characters
- Number of return sweep fixations/100 characters

Lengths and durations:

- Saccade Lengths:
  - *Length of forward movements: 1st, 2nd and 3rd quartiles (Len-ForMov)
  - Length of regressive movements: 2nd quartile (Len-RegMov)
  - Length of forward in regression movements: 2nd quartile
  - Length of return sweep movements: 2nd quartile
- Movement Durations:
  - Duration of forward movements: 1st and 2nd quartiles (Dur-ForMov)
  - Duration of regressive movements: 2nd quartile
  - Duration of forward in regression movements: 2nd quartile
  - Duration of return sweep movements: 2nd quartile
- Fixation Durations:
  - *Duration of all fixations: 1st, 2nd and 3rd quartiles (Dur-TotFix)
  - *Duration of forward fixations: 1st, 2nd and 3rd quartiles (Dur-ForFix)
  - Duration of regressive fixations: 2nd quartile (Dur-RegFix)
  - Duration of forward in regression fixations: 2nd quartile
  - Duration of return sweep fixations: 2nd quartile

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*These variables served as the dependent variables in Window Experiments III and IV.

Effects of Peripheral Text Patterns. For each of these variables, eight 3-way analyses of variance were carried out, one for each window size. The purpose of each analysis was to determine whether at that window size peripheral text pattern had any effect on the dependent variable. The three factors in each analysis of variance were subjects (six), letter replacement algorithm used in producing the peripheral text pattern (called Letter Replacement, with three levels for C, NC and X versions), and whether the peripheral text pattern had spaces and punctuation remaining or removed (called Space vs. Filled, with two levels for S and F versions). This led to a large number of analyses, a total of 272, being carried out. Since this was bound to lead to a number of significant effects on the basis of chance alone, the following strategy was used to identify differences which were likely to be reliable. A difference was considered to be reliable if it occurred at two successive window sizes, with a significance level less than .10 at each window size, and with the data pattern at both window sizes being similar.

For most dependent variables there was a significant main effect for subjects, and for some, subjects interacted with other variables. These effects will not be explored here, but attention will be given to main effects for Letter Replacement and for Space vs. Filled, and interactions between these two variables.

For window sizes of 31 and greater there were no reliable effects using the above definition of reliability. Where significant effects were found at one window size, the data pattern observed at adjacent window sizes was not the same. Thus these effects were assumed to be due to chance factors. It is concluded that with a window size of 31, there is no evidence that the readers were acquiring either word shape or word length pattern information from the region beyond the window. Thus, there is no evidence that this information was acquired more than 15 character positions from the point of central vision by the subjects of this experiment. One possible exception to this conclusion will be noted later.

A number of reliable main effects and interactions were found at the smaller window sizes. These are listed in Table 2. These could be broken down into four categories: variables that influenced saccade lengths, those that influenced the duration of fixations, those that influenced the number of regressions, and those that were more gross measures of eye behavior and hence were affected by the three categories already mentioned.

TABLE 2

WINDOW EXPERIMENT II: A LIST OF RELIABLE EFFECTS NOT INVOLVING THE SUBJECT FACTOR

Variable*	Window Size	Effect**	F Value	Degrees of Freedom	Signif. Level	Effect Seen in Figure
Tim-ForFix	17	S	31.60	1,5	.003	
	21	S	4.14	1,5	.10	
Tim-TotFor	17	S	30.33	1,5	.004	
	21	S	4.47	1,5	.09	
Num-TotFix	13	S	5.91	1,5	.06	
	17	S	11.49	1,5	.02	
	13	SL	3.29	2,10	.08	
	17	SL	3.41	2,10	.07	
Num-ForFix	13	S	19.06	1,5	.008	
	17	S	41.53	1,5	.002	
	21	S	4.60	1,5	.08	
Num-RegFix	13	L	5.67	2,10	.02	12
	17	L	3.87	2,10	.06	12
	25	L	5.60	2,10	.02	12
Len-ForMovQ2	13	S	3.94	1,5	.10	9
	17	S	13.36	1,5	.02	9
Len-ForMovQ3	13	S	21.87	1,5	.006	9
	17	S	24.79	1,5	.005	9
	21	S	18.65	1,5	.008	9
	25	S	6.27	1,5	.06	9
Len-RegMovQ2	13	SL	8.48	2,10	.007	10
	17	SL	8.01	2,10	.009	10
Dur-ForMovQ2	13	S	5.91	1,5	.06	
	17	S	9.35	1,5	.03	
Dur-ForFixQ1	21	SL	7.81	2,10	.009	11
	25	SL	8.00	2,10	.009	11
Dur-ForFixQ2	17	L	3.51	1,5	.07	11
	21	L	4.47	1,5	.04	11
Dur-RegFixQ2	21	L	5.58	1,5	.02	
	25	L	4.20	1,5	.05	

*Variables are listed in Table 1, together with mnemonics.

**S indicates significant effect for spaces vs. filled; L indicates significant effect for letter replacement; SL indicates a significant interaction.

Saccade lengths were affected only by the presence or absence of spaces in the peripheral text pattern. Figure 9 presents the average 1st, 2nd and 3rd quartiles for the distributions of saccade lengths for the S and F peripheral text patterns, together with an indication of the significant effects. As can be seen, when word length patterns were eliminated from the peripheral text pattern by filling the spaces, the saccades tended to be shorter. This effect is most noticeable at the 3rd quartile, indicating that it tended primarily to reduce the number of long saccades, thus constricting the distribution of saccade lengths at the high end, rather than simply shifting the entire distribution down. The difference between S and F versions is present at least up to a window size of 25, and may be present even further, though the difference there is not significant. It appears, then, that word length pattern information is acquired at least as far as 12 character positions (3^{o}) from the center of vision, and perhaps even farther, and is used in guiding the eye during reading.

A significant main effect for Spaces vs. Filled was also found for saccade duration data at the three smallest window sizes. With word length pattern eliminated from the peripheral text pattern, saccades were of shorter duration, which of course simply reflects the fact that saccades were of shorter distance under these conditions as already noted.

The average length of regressive saccades also tended to be less when word length information was eliminated from the peripheral text pattern, though the difference was significant only at window size 17. This difference is shown in Figure 10. The Spaces vs. Filled X Letter Replacement Interaction was significant at the .01 level for regression saccade length data at the two smallest window sizes, but the data pattern changed greatly between the two window sizes so these interactions will not be considered reliable or explored further. There was a tendency for the XS condition to produce particularly short regressive saccades at the 17, 21, and 25 window sizes, with saccade lengths for that condition being more like those of the Filled conditions than the other Spaces conditions.

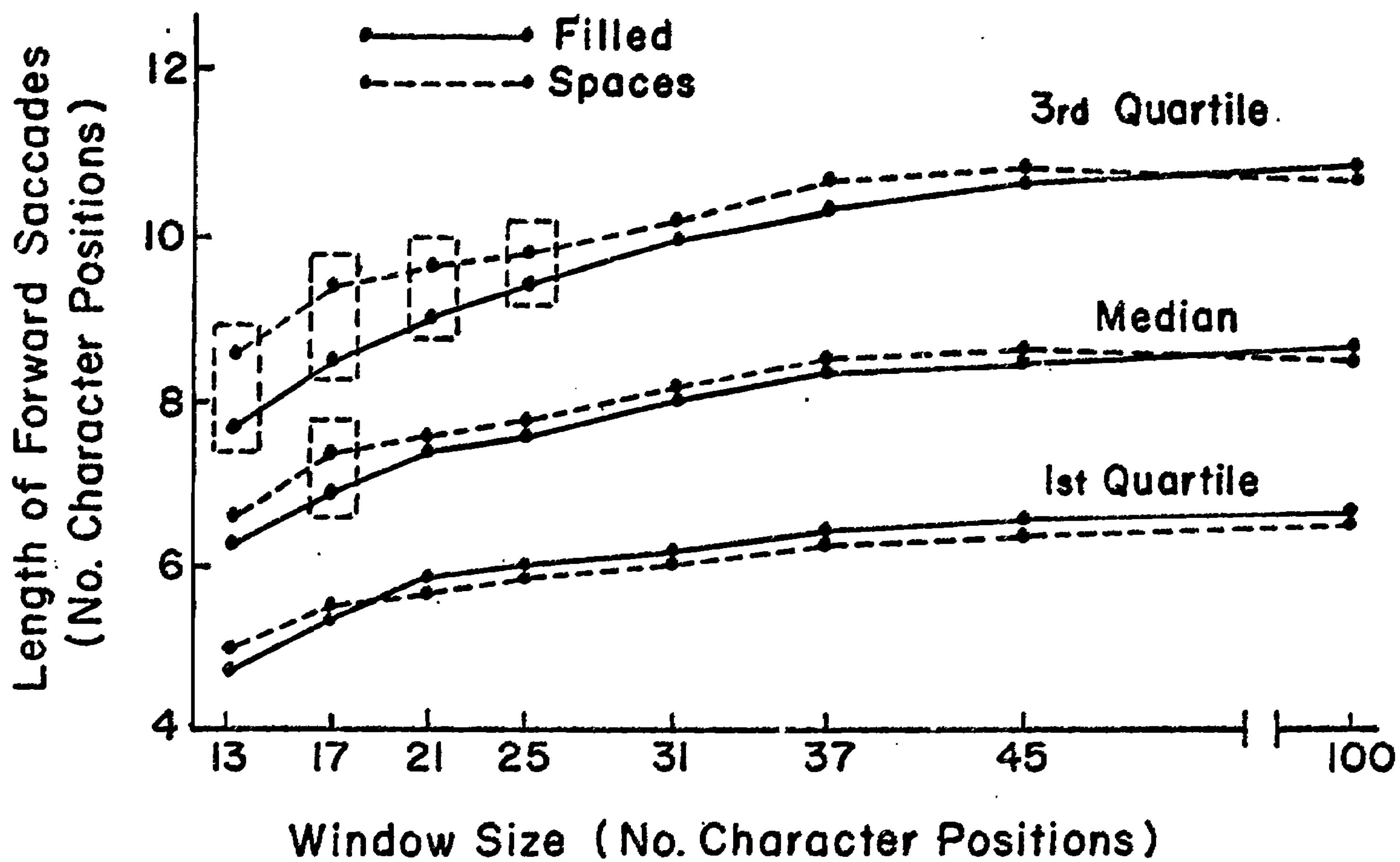


Figure 9 - Window Experiment II: The length of forward saccades as a function of window size and of the presence or absence of word length information in the peripheral text pattern; first, second and third quartiles.

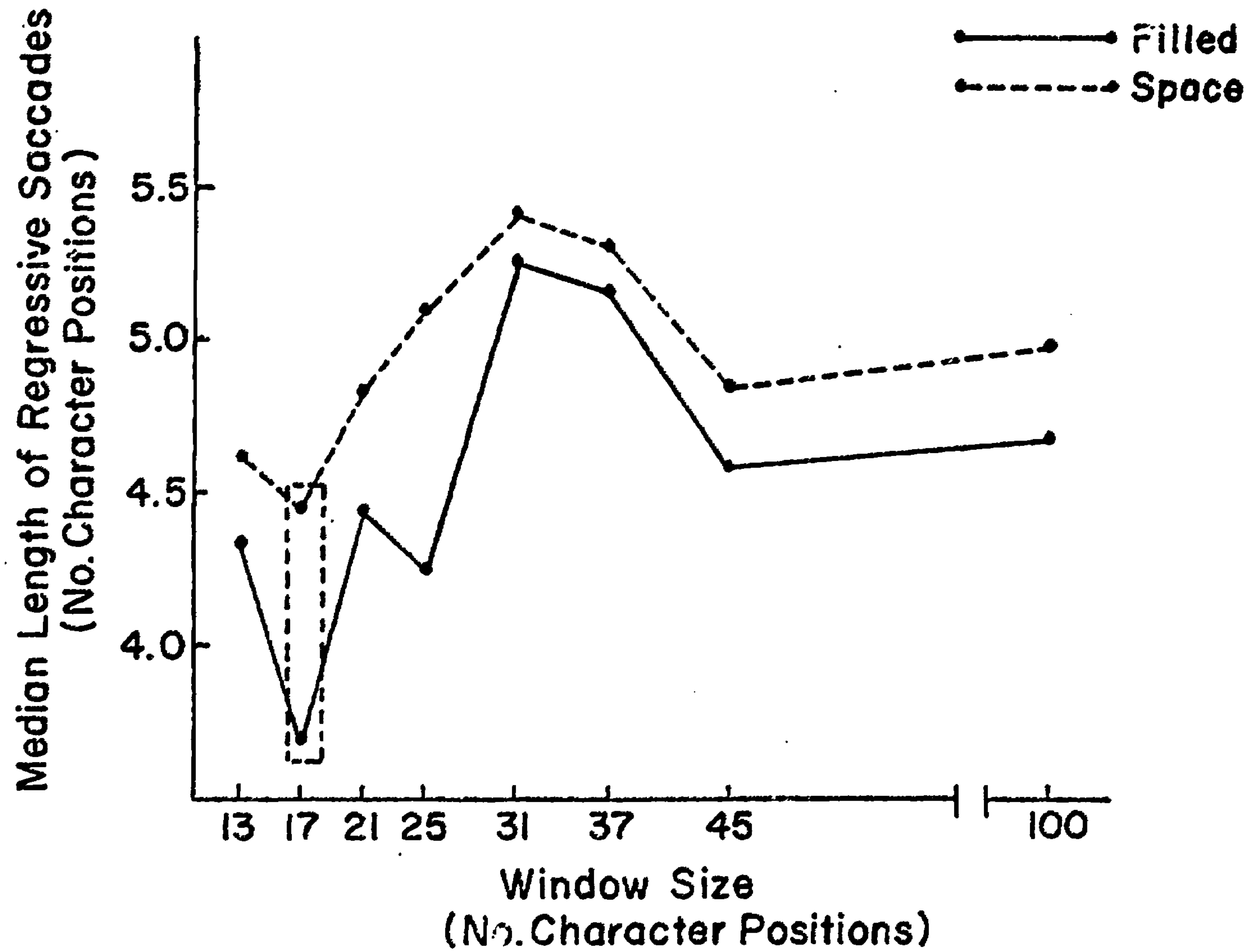


Figure 10 - Window Experiment II: The length of regressive saccades as a function of window size and of the presence or absence of word length information in the peripheral text pattern.

While lengths of saccades were influenced primarily by the presence or absence of word length pattern in the peripheral visual areas, the duration of fixations was influenced largely by letter replacement. Significant main effects for letter replacement were found for the 2nd and 3rd quartiles of the distributions of forward fixation durations and the 3rd quartile for total fixation durations at window sizes 1 and 21. The forward fixation duration data are presented in Figure 11. Total fixation duration data are almost identical. From this figure it can be seen that there tends to be a small difference in the duration of fixations between the C and NC letter replacement conditions at the two smallest window sizes, but that this difference disappears at window size 21. At the smaller sizes, having improper word shape patterns in the peripheral text pattern inflates the fixation durations slightly. With window size 21, however, it seems to make no difference whether the peripheral text pattern presents accurate or inaccurate word shape information, suggesting that general word shape information is not acquired by these readers as much as 10 character positions from the point of central vision.

At the three smallest window sizes, the X letter replacement condition leads to the lowest fixation durations. The X condition has the characteristic that the boundaries of the windows are well marked; the contrast between the normal text in the window region and the homogeneous x pattern in the peripheral area is very noticeable. Thus, it would seldom happen that a reader would make the error of attempting to integrate letters from outside the window into the text pattern within the window itself. On the other hand, with the C and NC letter replacement conditions the boundaries of the window are not at all obvious, and the reader undoubtedly quite frequently picks up letters from outside the window area and attempts to integrate them with the normal text in the window, thus producing some disruption. This disruption likely leads to the longer durations for the C and NC conditions as compared to the X conditions. If this is so, then the fact that there is a difference in fixation durations between the X and the C and NC conditions at window size 21 suggests that the reader is picking up specific letter information under the C and NC conditions as much as 10 character positions from his point of central vision. These differences disappear at window size 25, suggesting that this type of visual information is not being acquired by the readers at 12 character positions from the point of central vision.

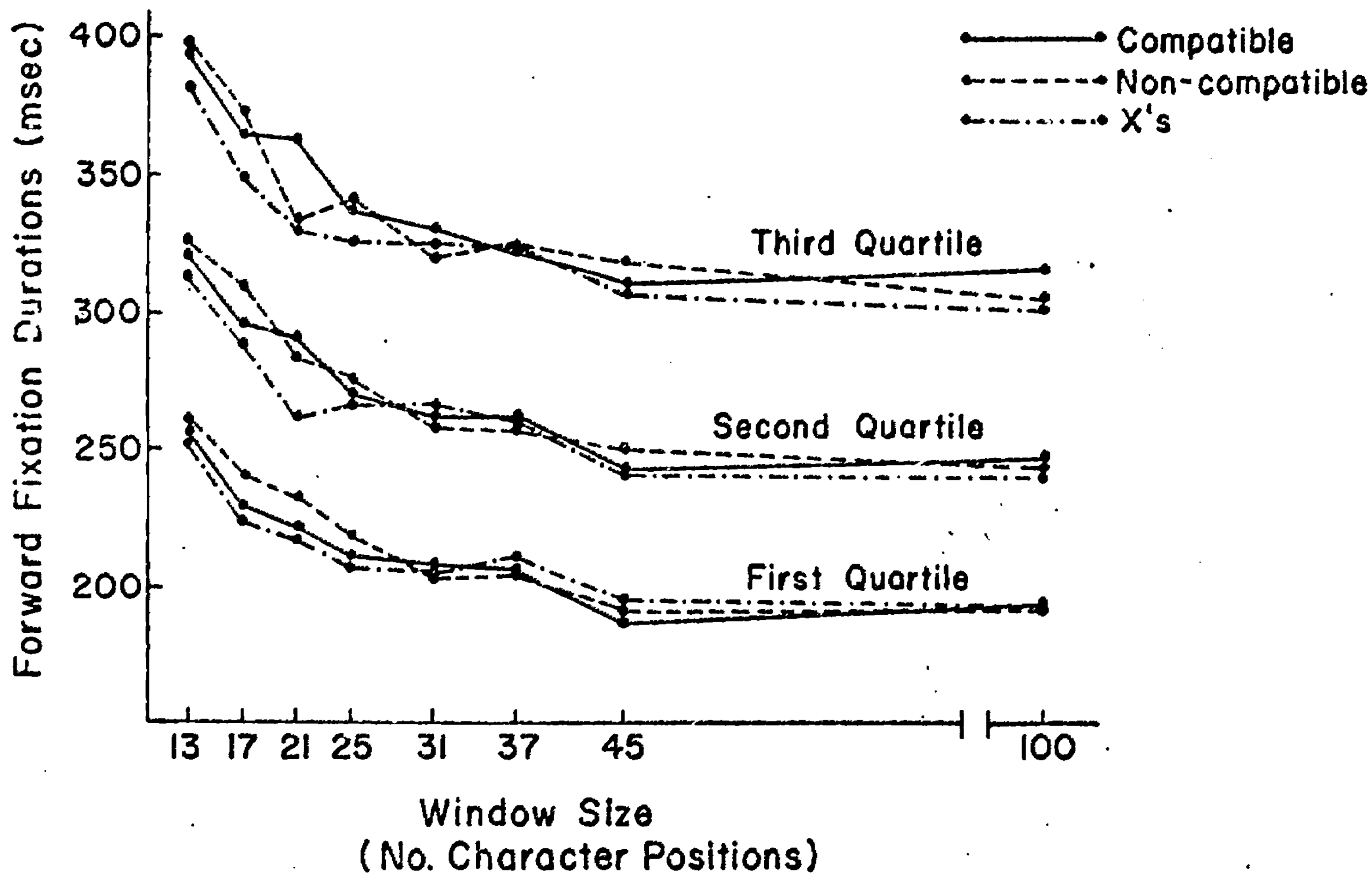


Figure 11 - Window Experiment II: The duration of forward fixations as a function of window size and of the presence or absence of word shape information in the peripheral text pattern: first, second and third quartiles.

The first quartile forward fixation duration data showed a Spaces vs. Filled X Letter Replacement Interaction at window sizes 21 and 25. However, the data pattern was not consistent from one window size to the next, so these interactions will not be considered reliable.

This consideration of the fixation duration data leads to two conclusions: first, the subjects acquired specific letter information no more than 10 or 11 character positions (2 1/2°) from the point of central vision, and second, general word shape information was not acquired any further into the periphery than this, either. Thus, word shape patterns, other than word length characteristics, are acquired no further into the periphery than is specific visual information needed to identify letters.

The number of regressions made by subjects per 100 characters was reliably affected by the letter replacement pattern. Significant main effects for letter replacement were found at window sizes of 13, 17 and 25. These effects are shown in Figure 12. Here it is seen that the C condition produced the most regressions, whereas the X condition produced the least. The reason for this difference is not known, though it may have something to do with the naturalness of the appearance of the peripheral text pattern. The least natural-appearing pattern was the one which led to the fewest regressions.

The differences in saccade length, fixation duration, and number of regressions produced by the variables resulted in differences in other more gross measures of eye behavior in reading. A significant main effect for Spaces vs. Filled was found at window sizes 13 and 17 for total reading time per hundred characters, total time spent in forward movements and fixations per 100 characters, total number of fixations per hundred characters, total number of forward fixations per hundred characters, total time spent in fixations per hundred characters and total time spent in forward fixations per hundred characters. The latter variable also showed a significant effect at window size 21. These data will not be presented in detail since they simply resulted from the previously-noted effects of the variables on specific eye behavior measures and by themselves add nothing to the understanding of the reading processes involved.

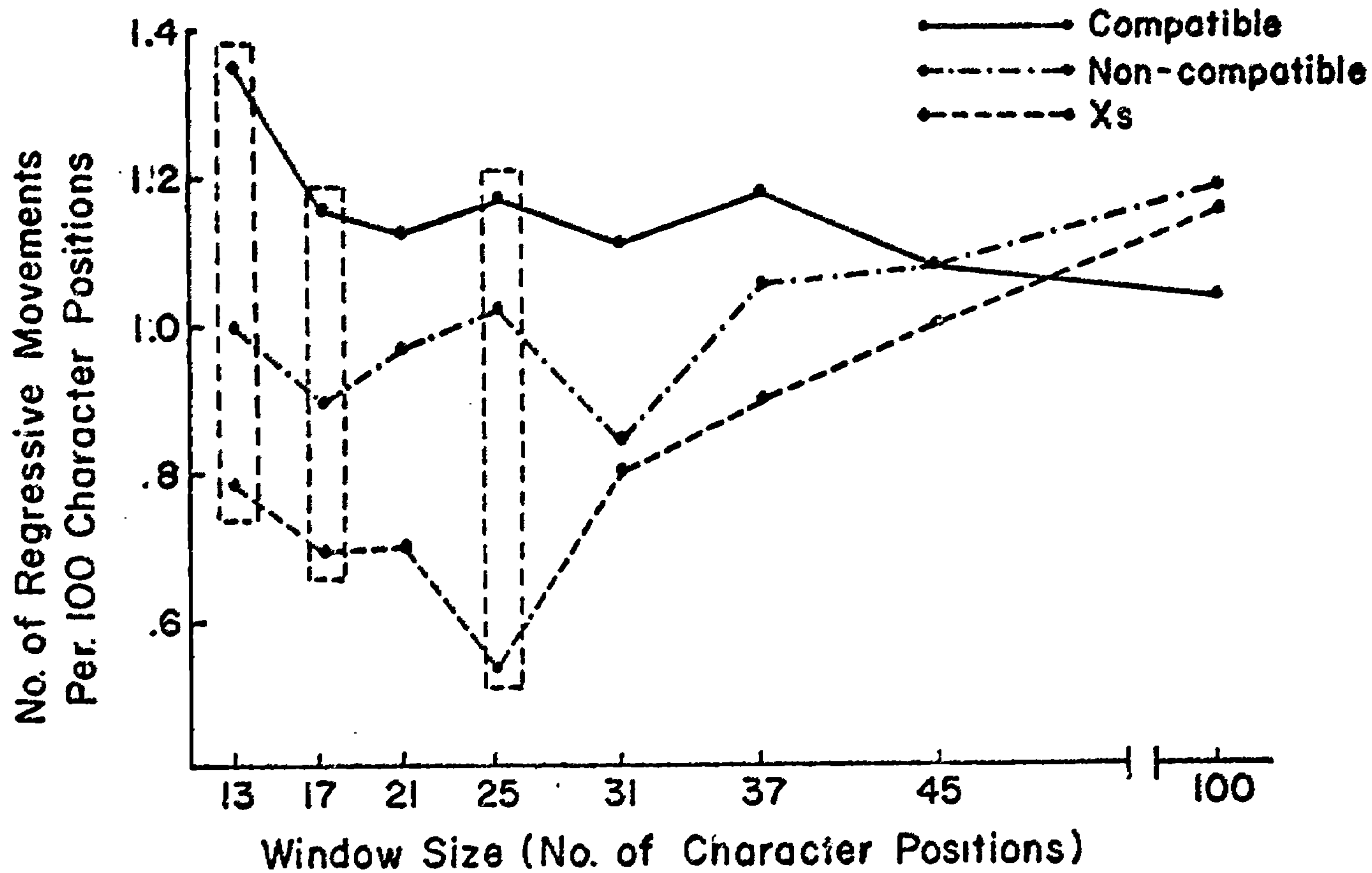


Figure 12 - Window Experiment II: The number of regressive movements per 100 characters as a function of window size and of the presence or absence of word shape information in the peripheral text pattern.

Effects of window size. Figure 13 shows the effect of window size on the time required to read the text. The dependent variable is time required to read one hundred characters. Reducing the window size caused this time to rise from 4.33 to 6.92 seconds, a 60% increase. This increase resulted primarily from an increase in the amount of time the eye was fixated: total time in movement rose 10% while total time spent in fixations rose 76%. As seen in earlier figures, this increase was a result of the subjects making both more fixations (a 33% increase from 12.82 fixations per hundred characters to 16.98) and fixations of longer durations (a 31% increase from 245 msec. median forward fixation duration to 320 msec.). The larger number of fixations was entirely the result of readers making shorter forward saccades, with median saccade length dropping from 8.71 to 6.43 character positions. There was no increase in the number of regressive movements as the window size was reduced. The median number of regressive movements per hundred characters ranged from 1.1 to .9 for the different window sizes. Thus, the increase in reading time with smaller window sizes was not due to a change in the number of regressions, but was the result of changes in the normal forward saccade and fixation pattern.

As seen in Figure 13, reading time continued to drop as window sizes became larger, and only reached asymptote at the largest sizes. Median saccade lengths and fixation durations showed the same pattern. This change may be due to either of two types of influences: either subjects were obtaining some useful visual information from the normal text from regions as wide as 45 character positions, which was not available in the peripheral text patterns, or else reducing the window size itself changed the reader's behavior or produced artifacts which were reflected in his eye movement behavior. The first of these possibilities would be of greatest interest, the possibility that the reader is actually acquiring and using certain specific aspects of the visual information from a very wide region around the point of central vision. However, this does not seem likely in view of the earlier-reported results from this experiment. The evidence seemed to indicate that the readers were not obtaining word shape or specific letter information from a region extending more than about 10 or 11 character positions from the point of central vision, and that they were not acquiring word length pattern information more than about 15 character positions into the periphery. If this is so, it is difficult to imagine what other visual characteristics of the text might be acquired further into the periphery which were not present in the peripheral text patterns. Therefore, it will be assumed that the continued drop in the reading time and other curves with increased window size has some other basis.

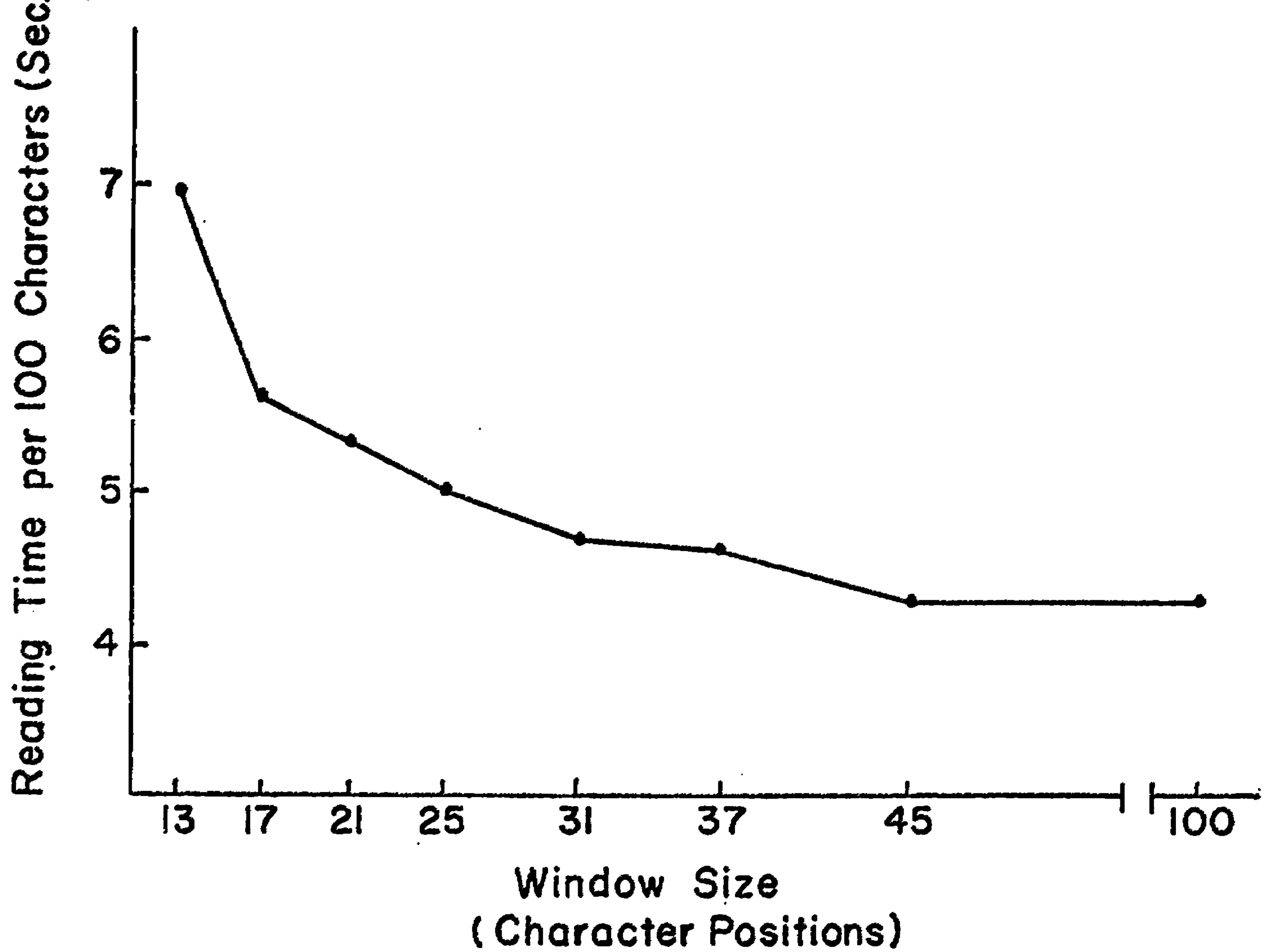


Figure 13 - Window Experiment II: Effect of window size on time to read 100 characters of text.

Among the many possible reasons for why reducing the window size might produce the effects noted, two seem particularly likely. One possibility is that subjects have the ability to control the size and location of the general area from which they acquire visual information on each fixation during reading. Thus, as the window became smaller, they tended to constrict their field of visual attention to a narrower region. This may also cause them to make shorter saccades and perhaps even longer fixations as the window becomes smaller, but at the same time would not lead to differences in reading behavior as a function of type of peripheral text pattern. If this explanation were in fact correct, it would invalidate the previous conclusions about the size of the region from which our subjects tended to pick up visual information; the results found would be typical only of subjects reading under conditions which forced them to narrow their range of attention during each fixation.

The second possibility for why smaller window sizes produced the effects noted is related to the lag discussed in Chapter 3 in identifying the onset of a fixation and producing the display changes required for this research. It was noted there that the display change may not have occurred for as much as 30 to 45 msec. following the actual eye fixation onset. Even though this is within the time when visual masking was likely occurring as one stimulus pattern replaced another, it is possible that the display changes taking place in the periphery were sufficiently distracting to produce changes in the eye movement patterns, causing longer fixations and producing more short saccades. With small window sizes, these changes would be taking place closest to central vision, where they might be expected to have the most disrupting effect. As the window became larger the changes were being made further and further into the periphery, where their effect, while still present, was reduced. Thus, reading patterns may have been effected somewhat by these display changes taking place even some distance from the point of central vision.

At present, the authors tend to accept this latter explanation. There are two reasons for this. First, Reder (personal communication) has conducted similar research at Rockefeller University under conditions with substantially less lag in producing the display change, and he reports that the curves asymptote much earlier in his studies. This suggests that the delayed asymptote in our research was not due to a narrowing of the field of attention, since if it were, the same phenomenon would be expected to be present in Reder's data. Rather, it is probably due to the relative slowness with which our display changes were taking place. Second, a study to be reported in a later chapter which did not involve the type of display changes used in the present study, and thus which would not tend to induce the reader to narrow his field of attention, obtained results concerning the size of the perceptual span in reading which are quite compatible with the estimates from the present study. This issue will be discussed further in Chapter 9, leading to the conclusion that the window size effects were probably due to artifacts produced by the display change itself, rather than to changes in the width of the field of attention.

Retention Test Performance. The retention tests were constructed to have two questions taken from the information on each page of text. This made it possible to carry out a four-way Analysis of Variance on retention test scores to determine whether the variables influenced the subjects' retention of information from the passages. The only significant effect was the Window Size X Subjects Interaction ($F = 1.553$, $p < .03$, 35 & 288 df). As in Window Experiment I, window size did not have any effect on text performance ($F = 1.371$, $p < .25$, 7 & 35 df). The significant interaction was plotted to determine whether there was a tendency for some subjects, but not others, to perform more poorly with smaller window sizes. No such tendency could be found. The interaction seemed to arise primarily from lack of complete counterbalancing in the experiment due to the small number of subjects in relation to the large number of passages. Curves for individual subjects were very irregular across window sizes, with no observable trends.

Thus, this experiment provides additional support to the notion that the poor comprehension of students with reading disabilities cannot be attributed to reading with a narrow perceptual span. Good readers who are forced to read from a narrow region of normal text succeed very well at retaining information from the text.

Discussion

This experiment has provided data which begin to answer the question about the size of the perceptual span during a fixation in reading. First it is clear that there is no single perceptual span, but that readers acquire and use different aspects of the available visual information different distances into the periphery. Of the aspects studied here, word length patterns seem to be acquired the greatest distance into the periphery, at least 12 character positions from the point of central vision and perhaps as much as 15 or more. There is no evidence that general word shape is being acquired further into the periphery than is visual information concerning specific letters. These types of information appear to be acquired no more than 10 or 11 character positions into the periphery. Assuming that word length patterns are used primarily in guiding the eye, these results suggest that the skilled reader acquires the type of visual information generally used for word and meaning identification from a rather narrow region during a fixation.

Several questions remain concerning the perceptual span. First is the question of whether the reader acquires useful visual information from the line other than the one he is directly fixating as he reads. Second is the question of possible asymmetry of the span; that is, does the reader acquire visual information equally far to the left and right of the point of central vision, or is there an asymmetry involved. Third is the question of whether the results obtained in the present study are peculiar to the situation where the subject is reading with a changing window, or whether the same general results would be obtained using quite a different research technique. These questions led to the studies to be reported in succeeding chapters.

CHAPTER 6

WINDOW EXPERIMENT III:
VISUAL INFORMATION FROM ANOTHER LINE

Researchers involved in the study of reading have long been interested in whether or not readers acquire and use visual information from lines other than the one being fixated. Dearborn (1906), for instance, suggested that word shape, dominant letters and word length of words in the line below the one being read may be of service in determining the location of fixation pauses in the second line. He also indicated that the reader may be getting some semantic information from that line, for he warns that "if the words in the line below have absolutely nothing or little to do with the sense of the line being read, this view is often more of a hinderance than a help."

Huey (1908) and Woodworth (1938) likewise suggested that information on lines other than the one being fixated may be useful to the reader.

More recently, the question has resurfaced in the study of selective attention in reading (Neisser, 1969; Willows and MacKinnon, 1973). Based upon the selective attention studies in listening (Moray, 1959; Treisman, 1964), the paradigm involves having subjects read text aloud which is double-spaced and which has words or phrases embedded between the lines. Willows and MacKinnon report that the information contained in the irrelevant lines do influence subjects responses on multiple-choice questions about the passage. Thus there is some evidence that subjects may semantically interpret information on other lines, at least at times.

In addition to this empirical work, Hochberg (1970) has suggested that the information available to peripheral vision from adjacent lines might be subject to preattentive processing, thus giving the reader a preview of what is to follow and facilitating his reading in that way.

The experiment to be described in this chapter was an attempt to use the Window Experiment technique to learn whether skilled readers obtain useful visual information from the line below the one being read. In addition, the study was designed to try to determine what aspects of the visual pattern were useful to the reader, if such facilitation were found.

In the study, subjects read with a wide window (40 character positions), and half the time the window included the line below that being read as well as the line being directly fixated. Thus, the window was either one or two lines high. In addition, several peripheral text patterns were used, varying whether or not accurate word shape and word length information was available in the region outside the window itself.

Method

Subjects. Six of the students who had participated in the previous experiments, three male and three female, served as subjects in this experiment as well. They were paid for their participation.

Materials. Eight 500-word passages were taken from the same high school psychology text as in the previous study. Each was divided into four pages, with each page containing 8 to 10 lines of text, and was presented double-spaced on the CRT. Four peripheral text pattern versions were prepared for each page of the text; these were of the same type as the CS, CF, NCS and NCF versions used in the previous study. Eight short-answer test questions were prepared for each passage, with two related to the information contained in each page of text.

Design. This study involved two window sizes and four peripheral text patterns. The peripheral text patterns have already been described. The window width was always 40 character positions, but sometimes it was restricted to the line being fixated and sometimes it included the line below as well. The factorial combination of these two variables resulted in eight experimental conditions. Since each subject read 32 pages of text, he was tested under each experimental condition four times. Conditions were balanced over passages and page sequence as far as possible.

Procedure. The procedure was similar to that in the previous studies. The study was conducted using the EYETRACK C program. Each subject was given the opportunity to read two or three passages to become reaccustomed to the experimental situation, and then he read the eight passages in the experiment, all in a single session. He was engaged in the calibration task prior to reading each passage, and was tested following each passage.

Results

Four-way Analyses of Variance were carried out for each of 13 of the dependent variables used in Window Experiment II. These variables are identified in Table 2. Factors for each analysis were Letter Replacement (C vs. NC peripheral text patterns), Spaces vs. Filled (S vs. F peripheral text patterns), Window Size (one or two lines) and Subjects (six subjects participated).

Every analysis showed a significant effect for subjects. All data of fixation durations indicated a significant effect for window size. Including the line beneath that being fixated in the window resulted in shorter fixation durations, as shown in Table 3. This apparently led to a significant effect of Window Size on the time required to read 100 characters ($F = 43.38$, $p < .002$, 1 & 5 df). The subjects read the text faster when the window included two lines. Time required to read 100 characters with a one-line window was 5.00 sec., but with two lines the time dropped to 4.84 sec.

There were few significant main effects due to either of the peripheral text pattern variables. A significant letter replacement effect was found for median saccade length for forward saccades ($F = 6.985$, $p < .05$, 1 & 5 df), but this effect was not significant for either the first or third quartiles for saccade length. A significant effect for spaces vs. filled was found for the first quartile of the distribution of total fixation durations ($F = 9.20$, $p < .03$, 1 & 5 df). This effect was not significant at either the second or third quartiles, nor was it significant for the first quartile of the distribution of forward fixation durations. In only two analyses was there a significant interaction between window size and either of the peripheral text pattern variables. One was a Window Size X Letter Replacement Interaction for first quartile data for the length of forward saccades. Neither the second nor third quartile data showed this pattern. The second was a Window Size X Letter Replacement X Spaces vs. Filled Interaction for total number of fixations per 100 characters. This interaction is shown in Figure 14. With a two-line window subjects required fewer fixations to read the passage when CF or NCS peripheral text patterns were present, but required more to read it when the CS and NCF patterns were used. The reason for this interaction is not apparent.

TABLE 3

WINDOW EXPERIMENT III: FIXATION DURATIONS WHEN READING WITH A ONE OR TWO LINE WINDOW

Variable*	Fixation Duration 1 Line	2 Lines	F**	Significance Level
Dur-TotFixQ1	209.75	198.75	9.90	.025
Dur-TotFixQ2	269.48	256.97	19.17	.008
Dur-TotFixQ3	343.49	329.22	18.07	.009
Dur-ForFixQ1	216.10	205.64	9.47	.027
Dur-ForFixQ2	272.48	260.52	22.58	.006
Dur-ForFixQ3	346.53	332.48	21.23	.007

*Variable mnemonics are listed in Table 1.

**All tests have 1 and 5 degrees of freedom.

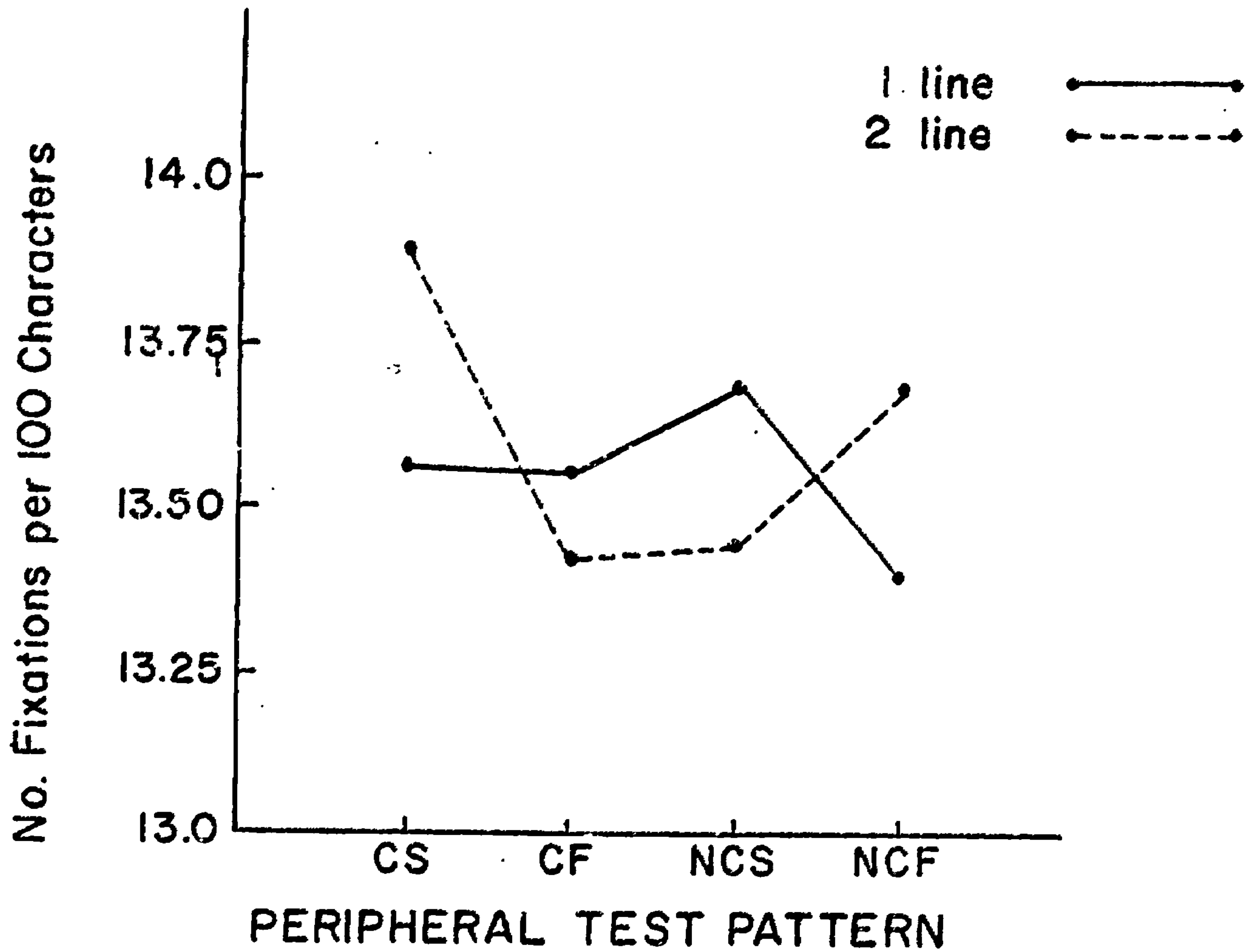


Figure 14 - Window Experiment III: Effect of window size and peripheral text pattern on total number of fixations per 100 characters.

Several significant interactions involving subjects was also present in the data. Subject X Window Size Interactions were found in both the fixation duration and saccade length data. First quartile data for fixation durations for both all fixations and for just forward fixations showed this interaction ($F = 9.90$, $p < .03$, 1 & 5 df; $F = 9.47$, $p < .03$, 1 & 5 df). Although all subjects showed shorter fixation durations with a two-line window, the amount of reduction was different for different subjects. First, second and third quartile data for the length of forward saccades each showed a significant Subject X Window Size Interaction ($F = 2.35$, 5.02 & 5.05; $p < .05$, .0005 & .0005; 5 & 144 df). Window size had a different effect on different subjects: four of the subjects showed longer saccades when the window contained only one line, and two showed longer saccades when it contained two lines. Thus, although the window size appeared to have an effect on saccade length, having the extra line present did not always lead to longer saccades.

One final interaction involving subjects was a Subject X Window Size X Letter Replacement Interaction for number of regressive movements per 100 characters ($F = 2.80$, $p < .02$, 5 & 144 df). The means involved in this interaction are presented in Table 4. No clear pattern emerged from its further examination.

TABLE 4

WINDOW EXPERIMENT III: MEANS FROM SUBJECT X NUMBER OF LINES X LETTER REPLACEMENT INTERACTION FOR NUMBER OF REGRESSIVE MOVEMENTS PER 100 CHARACTERS

	Confusable (C)		Non-confusable (NC)	
Subject	1 Line	2 Lines	1 Line	2 Lines
1	1.187	1.071	1.001	1.170
2	0.277	0.738	0.574	0.339
3	0.282	0.338	0.281	0.256
4	0.664	0.888	0.934	0.985
5	1.653	1.300	1.164	1.608
6	1.567	1.440	1.332	1.202

The results suggest that reading was indeed being effected by whether the line below the one being read contained normal text or not. The nature of this effect, however, was quite complex. The extra line shortened fixation durations for all subjects, but did not necessarily increase saccade length or have any effect on the number of regressions. Subjects did read the passages somewhat faster with the extra line of text present.

It is also not clear what the basis might be for any facilitation of reading which is present. In general, the peripheral text variables seemed to have little if any effect. There was no evidence that having word length or word shape information or the next line had any facilitative effect on reading. Thus there is no evidence that the reader facilitates his reading by acquiring either of these two types of information from one line as he reads the line above it. If any facilitative information is being acquired, then, it must be of a more detailed nature, such as specific letter information leading to some form of rudimentary semantic analysis. On the other hand, it may be that any difference found between reading behavior under the two window sizes is the result of some form of interference which takes place when the line below the one being read does not contain normal text.

At present, then, although we have some evidence that the nature of the stimulus pattern appearing on the line below the one being read has some influence on reading, which suggests that some form of visual information is being acquired from that line during reading, the basis for that effect is not at all clear. Thus, this question must wait for further research.

CHAPTER 7

WINDOW EXPERIMENT IV: ASYMMETRY OF THE PERCEPTUAL SPAN

In the experiment to be reported in this chapter, we were interested in learning whether readers acquire visual information from a symmetrical region around central vision on the line being read, or whether this region tends to be asymmetrical. This question is related to recent research on the nature of the scanning mechanism in word recognition. Studies by Mishkin and Forgays (1952), Heron (1957), Bryden (1960) and others have generally found that words and letter strings displayed tachistoscopically are recognized better if they are presented to the right of the fixation point than if they are presented to the left of it. Although there is some controversy about the explanation for this result, with some possibility that order of report artifacts may be involved, still it is generally believed that it is due to a tendency for subjects to be poised ready to begin their scan of the word near their fixation region (Neisser, 1967; White, 1969). When the stimulus is presented to the left of the fixation point, the subject must redirect his scan to begin further to the left and the time required to do this leaves less time for word identification itself. Since the stimuli were presented tachistoscopically, this scan is obviously not an eye movement, but rather is an internal attentional scan.

If it is true that subjects tend to normally begin their scan near central vision, and if this is not simply the result of requiring subjects to fixate a point in tachistoscopic studies, this would suggest that readers may tend to acquire visual information primarily from the right of central vision during a fixation. The study to be described here was an initial attempt to test this hypothesis.

The window method was again employed. Three window conditions were used in the study. The first was a wide, centered window (41 character positions), presenting text 20 character positions to left and right of the fixation point during each fixation. The second was a narrower window, 25 character positions in width, which was shifted 8 character positions to the right. This window then extended 20 character positions to the right of central vision, as the first window condition did, but only 4 character positions to the left. Thus character positions 5 to 20 to the left of central vision, which were included in the first condition, were occupied by the peripheral text pattern in this second condition. The third condition involved a 25 character window, but this time shifted to the left. This window extended 20 character positions to the left of central vision as the first window did, but extended only 4 character positions to the right. An example of each window is shown in Figure 15.

The second and third window conditions, called the Right-shifted and Left-shifted conditions, had the same size window, and were equally eccentric with respect to the point of fixation. Thus, one question was whether subjects were capable to shifting their attention to base their reading on the visual pattern in one region of the retina as well as another. Also, the centered window condition provided a baseline to determine the degree to which subjects were hampered in their reading under the two shifted-window conditions.

Method

Subjects. Three students who had participated in the earlier studies served as subjects in this experiment as well.

Materials. Six passages of approximately 500 words each were extracted from the same high school psychology text that had been used for the two earlier studies. Each was divided into six pages for presentation.

Design. Three window conditions and two peripheral text pattern conditions were used in the study. The window conditions have already been described: a centered 41 character position window and two 25 character windows, one shifted 8 character positions to the right, and one shifted 8 to the left. The two peripheral text patterns used were CS and CF, both having letters in the original text replaced with letters of similar visual appearance (confusable), with one having word spaces and punctuation remaining (CS) and the other having them replaced with a letter (CF). Factorially combining these variables produced 6 experimental conditions.

Each subject read all six passages, a total of 36 pages, with 6 pages of text in each experimental condition. Window condition remained constant for a subject through all pages of a passage, but peripheral text pattern alternated between pages. Window condition was counter-balanced over passages.

Procedure. The procedure was similar to that of previous studies. Data for each subject were collected in a single session.

Window Type	Example*
Centered	Cnojkaiazy means personality diagnosis from hand wnlflrz. Ykle le o
Right-shifted	Cnojkaiazp wsorc jsncaroiity diagnosis from hand wnlflrz. Ykle le o
Left-shifted	Cnojkaiazy means personality diagnaeie tnaw dori mnlflrz. Ykle le o

*All windows are as they would be if the subject fixated the letter d in the word diagnosis.

Fig. 15. An example of the three window conditions used in Window Experiment IV.

Results

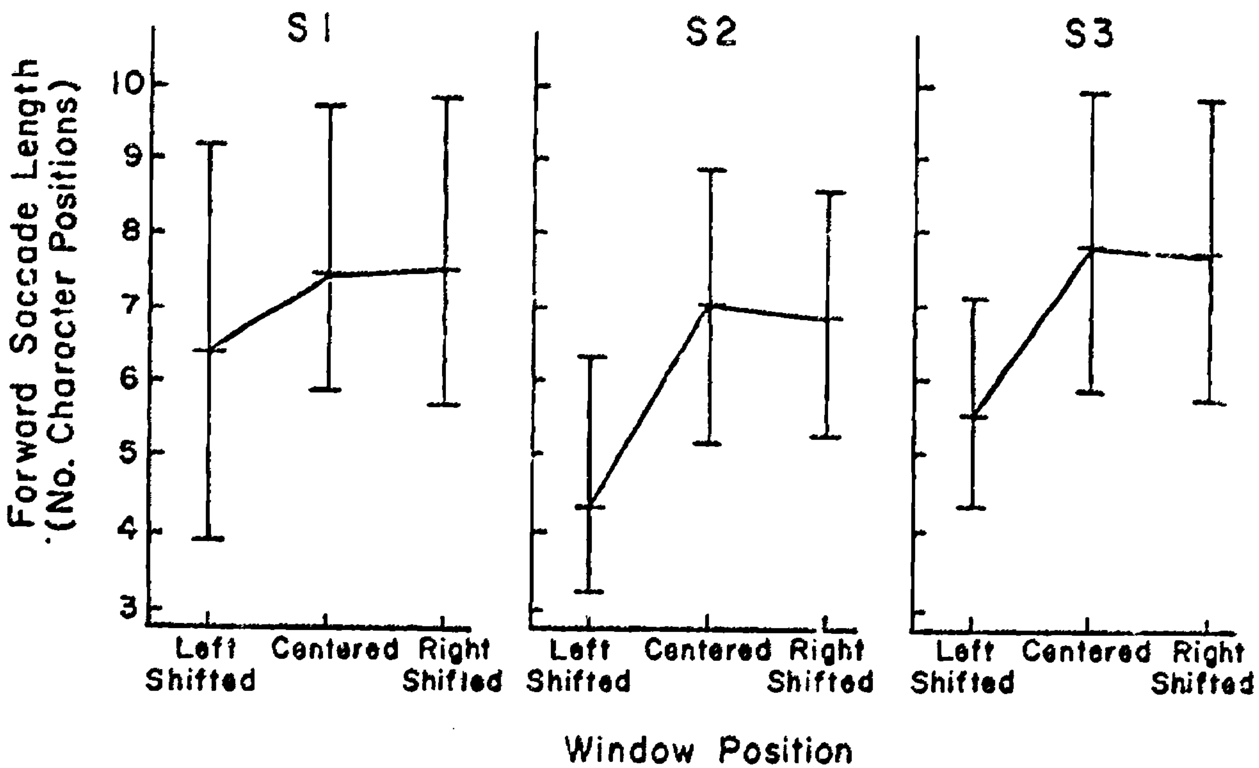
Three-way Analyses of Variance were carried out for 13 of the dependent variables listed in Table 1. Factors for each analysis were window condition, peripheral text pattern, and subjects. The main effect due to subjects, and the Subject X Window Condition Interaction were significant in every analysis, usually at the .0001 level, and the main effect for window condition was significant in three of the analyses at least at the .05 level. The peripheral text pattern variable produced no significant main effects nor did it enter into any significant interactions.

The general pattern of the data throughout these analyses can be summarized as follows. For every dependent variable, the centered window and right-shifted window conditions showed very similar data values. The data for the left-shifted window were almost always deviant from the others. This deviance sometimes failed to show up as a main effect for window condition, because different subjects reacted differently to the left-shifted window. The data for two subjects were consistently quite similar. The third had much greater difficulty reading under the left-shifted window condition, and showed quite a different data pattern altogether, with a very large number of regressions, reading time which quadrupled as compared to 24% and 28% increases for the other subjects, and fixation durations which shortened as compared to rising for the other subjects.

Saccade length for forward saccades showed significant effects for subjects, window condition and for Subject X Window Condition Interaction second and third quartile data, and the main effects were significant for the first quartile data. Figure 16 shows these data plotted separately for subjects.

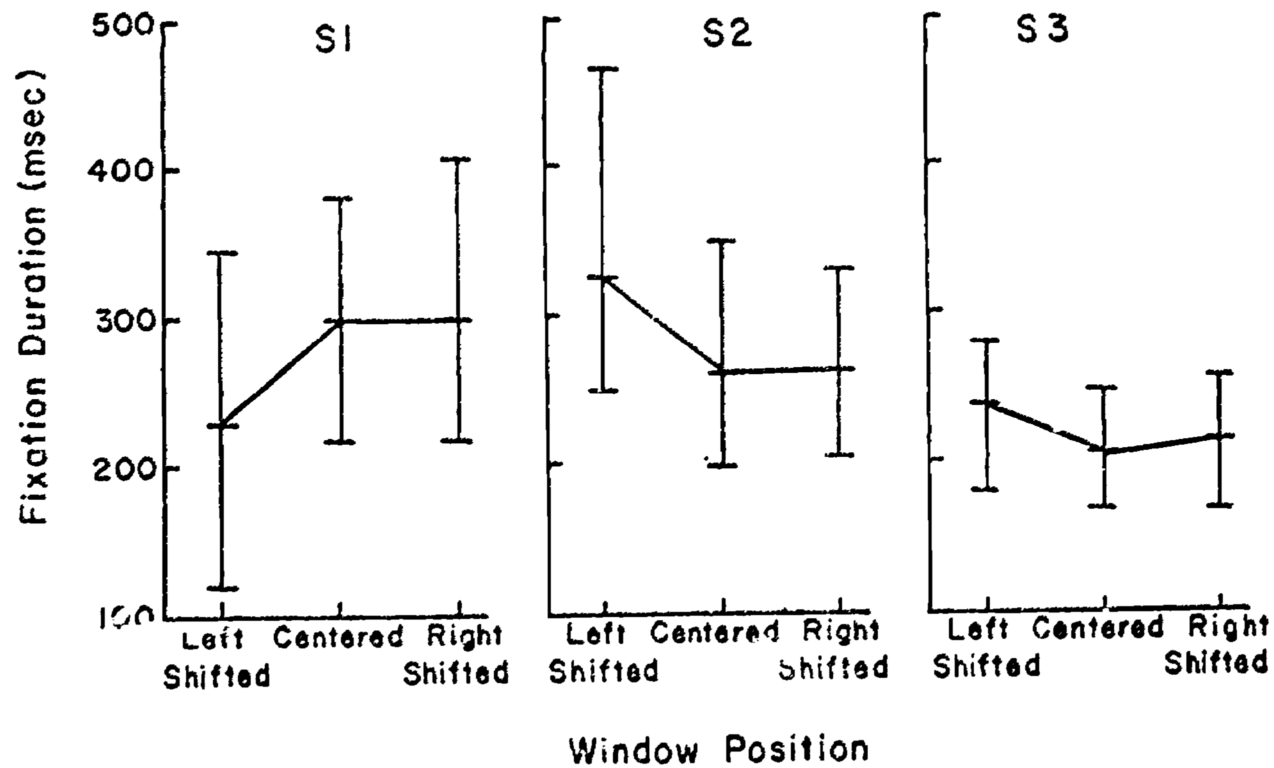
First, second and third quartiles for the distributions of fixation durations all showed significant effects for subjects and for the Subject X Window Condition Interaction. Figure 17 presents these data.

Finally, the number of regressive movements per 100 characters is shown in Figure 18. Again, effects for subjects and for the Subject X Window Condition Interaction were significant.



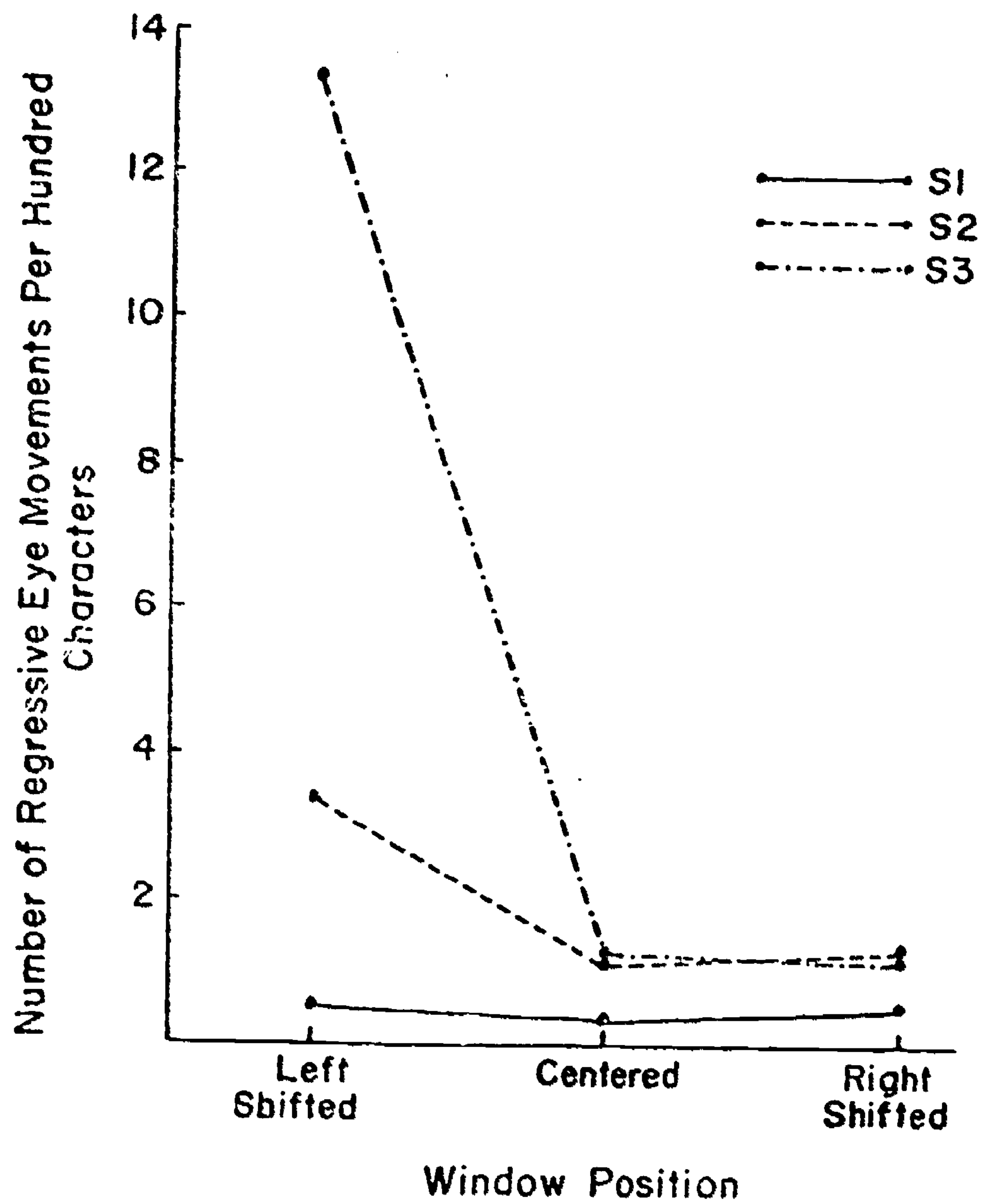
Note - Centered windows were 41 character positions wide. Shifted windows were 25 characters wide and offset 8 character positions in the direction indicated.

Figure 16 - Window Experiment IV: Effect of window condition on forward saccade lengths of individual subjects; first, second and third quartiles.



Note - Centered windows were 41 character positions wide. Shifter windows were 25 characters wide and offset 8 character positions in the direction indicated.

Figure 17 - Window Experiment IV: Effect of window condition on fixation durations of individual subjects; first, second and third quartiles.



Note - Centered windows were 41 character positions wide. Shifted windows were 25 characters wide and offset 8 character positions in the direction indicated.

Figure 18 - Window Experiment IV: Effect of window condition on number of regressive eye movements for individual subjects.

Discussion

The results of this experiment demonstrate a substantial asymmetry in the reader's perceptual span. Removing the normal text pattern leftward from a point four character positions to the left of central vision produced little or no effect on the subjects' reading behavior. Removing normal text from a similar region to the right of the fixation point substantially changed the reading patterns for all three subjects, and was particularly disruptive for one subject. It can only be concluded that for these subjects reading was being carried out primarily within the region of central vision and to the right of it. There was no evidence that subjects acquired useful visual information further to the left of their fixation point than 4 character positions. It may be that they did not use visual information even that far to the left, but this possibility requires further study. It also appears possible that skilled readers use visual information from the right half of the retina only at certain times, such as on the fixation following a return sweep, and that most of the time reading is carried out entirely in the left half of the retina. Again, this speculation requires specific study, but if so will have implications for the study of cortex hemispheric specialization.

CHAPTER 8

BOUNDARY EXPERIMENT: METHOD

This chapter will describe the last of this series of experiments conducted in our attempt to identify the region from which skilled readers acquire visual information. This study was an attempt to use another technique to replicate and extend some of the findings reported in Chapter 5, concerning the distance into the periphery that word shape and specific letter information are acquired during a fixation. The method used was one which minimized the amount of display change occurring, thus reducing the likelihood of causing the reader to narrow his range of attention. It was also an attempt to produce these display changes during the time a saccade was underway, though as explained in Chapter 3 a characteristic of the equipment and eye sampling rate made it probable that most or all display changes were occurring shortly after the saccade ended. Still, the lag in producing the display change was shorter in this study than it had been in the window studies. With these changes in the method used, it was felt that the results were less likely to be influenced by artifacts that may have influenced the results of the window study.

As indicated earlier, the method used in this experiment, called the Boundary Study, involved changing the stimulus pattern only once as the subject read a paragraph, and that change was limited to the stimulus in a single word location, called the Critical Word Location (CWL). This stimulus change was triggered when the eye crossed a boundary set on the line containing the CWL. When this occurred, the stimulus pattern initially displayed in the CWL was replaced by the Base Word, the word which was originally written into the paragraph. The initially displayed stimulus patterns had certain visual characteristics in common with the Base Word in the different conditions. Two aspects of the data were examined. First, the durations of the fixations prior to the stimulus change were analyzed to determine how far from the CWL there was evidence that the subjects' reading was being disrupted by the presence of a non-word letter string in that location. Second, the duration of the first fixation following the stimulus change was examined to determine under what conditions the subjects noted the stimulus change.

An example of the display change is shown in Figure 19. Line I shows the sentence as it originally appeared when first displayed. The location of the boundary is marked with a B here, although, of course, no such indication was present in

I. The robbers guarded the pcluce with their guns.
1 B

II. The robbers guarded the palace with their guns.
B 2

Key: B - Location of the boundary which triggers a change in the display.

1 - Location of the last fixation prior to crossing the boundary.

2 - Location of the first fixation after crossing the boundary.

Fig. 19. An example of the type of display change which occurred in the Boundary Experiment.

the original passage. The last fixation the reader made prior to crossing the boundary is marked with a 1. Line II shows the same line as it appeared on the next fixation. Here, the fixation point is marked with a 2, which is the first fixation after crossing the boundary. Since the subject crossed the boundary on the preceding saccade, the initially displayed alternative is now replaced by the Base Word, palace.

Method

Subjects. Ten undergraduate students at the Massachusetts Institute of Technology, six male and four female, served as subjects. They were recruited from a subject pool list kept by the Department of Psychology and paid $2.00 an hour for their services. They were told that the purpose of the study was to determine what people look at when they read, and that their eye movements would be monitored and recorded by a computer. All of the subjects had normal, uncorrected vision.

Materials. A set of 225 sentences was prepared, with each sentence being of the following grammatical form (ignoring function words and auxiliaries):

(Sentence: Subject + Verb + Object + Prepositional Phrase)

In all cases the surface structure subject corresponded to the deep structure subject. In most cases, the subject also took the role of an animate agent according to the case grammar notions (Fillmore, 1968) and the object was either patient or instrument. One of the word locations in each sentence was identified as the critical word location (CWL) and five alternative words or letters strings were prepared which could be inserted into that area. For example, if the critical sentence were:

The robbers guarded the ________ with their guns.

the first alternative was to have the original word, called the Base Word, in the CWL. In this example the Base Word was palace. Since this alternative was a word, and was identical to the Base Word, this condition was called W-Ident. The second alternative was another word (police) which fit into the sentence both semantically and syntactically, and which began and ended with the same letters and maintained the basic external word shape of the Base Word. This condition was called W-SL since it was a word (W), and both word shape (S) and extreme letters (L) were identical to the Base Word. In the remaining three conditions, the alternatives were all non-word (N) letter strings which bore certain graphic similarities to the Base Word. In the N-SL condition the alternative (pcluce) maintained both extreme letters and word shape. Word shape was preserved by substituting letters that were visually confusable for certain letters in the W-SL alternative. The W-Ident and the W-SL alternatives were compared and all of the letters that were common in the two W alternatives were left untouched in the N-SL alternative. Every letter that differed in the W alternatives was replaced, in the N-SL, by a letter that was visually confusable with the letter in the W-SL alternative. In addition, ascenders were always replaced by ascenders and descenders by descenders. For the N-L condition, the alternative (pyctce) was formed by replacing every letter, except the extreme letters that were common to both W alternatives, with letters that are not visually confusable and did not share prominent distinctive features. For example, a descender was replaced by an ascender or a letter that did not extend below the line. Thus, the shape of the Base Word was destroyed in the N-L condition but the extreme letters remained the same. In the final condition, N-S, the alternative (qcluec) was formed by comparing the W-Ident and W-SL alternatives. Any letter in the middle of the word that was the same in both W alternatives was left the same, but every other letter was replaced with a letter that was visually confusable with its corresponding letter in the W-SL. Therefore, in this condition the word shape was maintained but the extreme letters were changed. The confusable letters were determined from a confusability matrix and grouping (Bouma, 1972). The sentences were so constructed that the original words in the CWL's were equally often 5, 6, and 7 letter words, and served as subject, verb, and object in their respective sentences equally often. Table 5 shows one example of each type of Base Word and the other four initially displayed alternatives.

TABLE 5

BOUNDARY EXPERIMENT: EXAMPLES OF BASE WORDS AND INITIALLY DISPLAYED ALTERNATIVES

Grammatical Category	Number of Letters	Base Word	Initially Displayed Alternatives				
			W-Ident	W-SL	N-SL	N-L	N-S
Subject	5	girls	girls	grads	gvobs	gbfns	pvobr
Subject	6	tailor	tailor	trader	tvobcr	tbfnir	fvobcv
Subject	7	planter	planter	plumber	plmnder	plktrer	qtmndcv
Verb	5	bowed	bowed	bound	bomud	bokdd	damub
Verb	6	tested	tested	tasted	tosted	tflmed	fostab
Verb	7	cracked	cracked	crushed	crmrbed	crklwed	evmrbcb
Object	5	ruler	ruler	rotor	ratar	rymyr	vatan
Object	6	palace	palace	police	pcluce	pyctce	qcluec
Object	7	protest	protest	product	probmet	prynkjt	qvobmel

Each of the 225 sentences was embedded into a short paragraph by writing two or three other sentences which could serve as a reasonable context for it when either of the W alternatives occurred at the CWL. All paragraphs were about 35 words in length, requiring 3 lines, and the CWL occurred equally often in the first, second, or third line of the paragraph. In order to control for one of the two W alternatives being more predictable than the other, for most W alternative pairs two paragraphs were written in which both words could reasonably fit. Then the selection of which word to use as the Base Word, and hence as the W-Ident alternative, for each paragraph was made randomly. Where a single passage was written for a W alternative pair, the choice as to which word would function as the W-Ident was also made randomly.

For each block of 15 paragraphs, a test was constructed consisting of a set of 12 sentences. Of the 12 sentences, 6 were actually taken from the paragraphs that the subject had just read. Of those, 2 were sentences that the CWL had appeared in and the other 4 were non-CWL sentences. The 6 distractor sentences included 3 sentences that had no relationship to any of the paragraphs read and 3 sentences that were taken from other blocks of 15 paragraphs that the subject had either previously read or would read. With these latter types of sentences, the sentences containing the CWL were never used. Also, a few words in each of these latter sentences were changed so that they were not identical to the original. There were always three blocks of 15 paragraphs each between the location of a sentence in the presentation sequence and where a modification of it appeared in a test as a distractor sentence. On this test, subjects were asked to identify which sentences had been taken from the block of paragraphs they just read.

Procedure. The paragraphs were presented to the subjects one at a time, triple spaced, on the cathode-ray tube. The subject's eyes were monitored using the EYETRACK D routine described in Chapter 3. This routine allowed the experimenter to provide the computer with a list of boundary locations and initially-displayed alternatives to be used for successive paragraphs, and it then took the reader through the experimental sequence, first presenting the calibration task, then presenting the paragraphs one at a time while recording eye behavior, and making the stimulus change at the appropriate time for each paragraph. After reading a block of 15 paragraphs, the subject came off from the bite bar and was given a sheet of containing the list of test sentences for that block. He was asked to mark the sentences which were taken from that block of paragraphs.

The eyetracking equipment was adjusted for each subject, he was given the opportunity to read two or three passages in the equipment, and he then read fifteen blocks of fifteen paragraphs each within a single session lasting about two hours.

Design. The independent variables in this study were of two categories, CWL word types and experimental conditions. There were two word type variables, word length (5, 6 or 7 letters) and part of speech (subject, verb or object). There were also two experimental condition variables: CWL alternatives (W-Ident, W-SL, N-SL, N-L, or N-S) and boundary locations. Five boundary locations were used: (1) 9 character positions to the left of the 1st letter of the CWL, (2) 6 character positions to the left of the CWL, (3) 3 character positions to the left of the CWL, (4) directly on the 1st letter of the CWL, and (5) on the 4th letter of the CWL.

The paragraphs were presented in the same order to all subjects and the word type variables were nested in paragraphs. That is, the Base Word in the CWL in each paragraph was of a certain length and part of speech. Thus, these variables were confounded with presentation sequence and paragraphs. For the order of presentation, a paragraph sequence was viewed as being in blocks of 9 paragraphs. Within each successive block of 9 paragraphs, all word type combinations were represented and sequenced in a random order.

For the experimental conditions, 5 condition orders were constructed. Since there were 5 possible locations and 5 CWL alternatives, the factorial combination of these meant that the CWL in each paragraph could be presented in any of 25 possible conditions. For each paragraph, five of the 25 possible presentation conditions were selected in the following manner. The sequence of 225 paragraphs were considered to be grouped into blocks of 5 successive paragraphs each. The 5 conditions for a particular paragraph to be tested under were selected by using a series of 5 X 5 Greco-Latin squares. Five successive paragraphs were assigned to the rows of a particular square. The first digit in the number contained in each cell of the square identified a CWL alternative; the second identified a boundary location. The five cells in a row indicated the 5 experimental conditions which a particular paragraph would be tested under. The five columns identified five experimental condition sequences for those five paragraphs. Combining this information for all paragraphs produced 5 experimental condition sequences to be used in the experiment. The sequences had the property that each paragraph was tested under each value of each of the two experimental variables, CWL alternative and boundary location, though not in all combinations of these. However, within each block of 5 paragraphs, one of the paragraphs was tested under each of the 25 experimental conditions. Since there were 10 subjects, each of the five experimental condition sequences was used for two subjects.

For the actual presentation sequence, the paragraphs were grouped into blocks of 15. Thus, a block of 15 paragraphs contained all nine word type combinations at least once, with six of the combinations occurring twice.

Over the 15 blocks of 15 paragraphs, each subject was tested equally often with each of the word types and under each of the experimental conditions. Each of the 25 experimental conditions occurred nine times for each subject, and each of the nine word type conditions occurred 25 times.

CHAPTER 9

BOUNDARY EXPERIMENT: RESULTS

This chapter will present the results of the Boundary Study. The chapter is divided into six sections. The first section presents a general overview of the major dependent variables in the study. The second section deals with the amount of visual attention that the subjects allocated to different areas of the line containing the CWL. The third section investigates whether actually seeing the display change take place may have influenced the results. The fourth section presents the main results of the experiment, having to do with the effects of the graphical changes on reading behavior. The final two sections deal with the effect on reading behavior of the part of the speech of the Base Word in the CWL and the number of letters in the CWL.

Overview of the Dependent Variables

In this study it was expected that the alternative letter strings appearing initially in the CWL would produce some form of disruption of the normal reading pattern. There were two types of disruption anticipated. The first involved no change in the display. It was assumed that if the reader encountered a non-word letter string in his reading this would lead to a disruption in the normal cognitive processes, probably marked by an inflated fixation duration as the unsuccessful attempt was made to match the visual pattern to a semantic interpretation. The question for study was how far from the CWL this disruption of the eye behavior pattern would be noted; that is, how close must the fixation be to the CWL before a fixation duration difference would be noted between those instances when a non-word occupied the CWL and when a word occupied that location. This, then, would indicate how far into the periphery the readers detected the difference between a word and a non-word, which would indicate how far from central vision they were making a semantic interpretation of the visual pattern.

The second type of disruption that was expected was that resulting from a change in the visual display. As indicated in Chapter 2, it was assumed that subjects integrate the visual information from successive fixations into a single visual image, and that certain aspects of that image are then extracted for use in identifying the meaning of the text. This led to the assumption that if a subject acquired certain visual features from a certain word location on one fixation, and then on the next fixation the stimulus pattern in that location had been changed so the features he had previously obtained were contradicted by the features of the new pattern, this would lead to a reanalysis of the stimulus pattern in that region which would likely result in an inflated fixation duration. It was also thought that it might lead to regressive eye movements on later fixations as well.

On the other hand, if the visual features he had acquired on the first fixation were consistent with the new visual pattern following the stimulus change, the change would not be detected, and hence it would have no effect on the eye movement pattern. Given these assumptions, the task became one of examining the fixation durations of the fixations which occurred immediately after the stimulus change was made to determine under what conditions there was evidence of such a disruption; that is, under what conditions did a stimulus change result in a longer fixation duration than did no stimulus change. For the present study these "conditions" included the type of stimulus change made, and the distance of the previous fixation from the CWL, the location of the stimulus change.

Thus, the analysis of the data focused primarily on the duration of the fixation just prior to the display change, and that just after the display change, plus the regressions which occurred on later fixations.

Before turning to these analyses, two questions will be considered. Generally within what range around the CWL did the readers tend to show increased fixation durations? And, is there evidence that the subjects were seeing the stimulus changes themselves take place, and that this was producing certain features of our data?

Fixation Durations for Fixations at Different Distances from the CWL

The first task was to obtain some general information concerning the size of the region around the CWL in which reading disruptions were taking place as a result of the variables in the study. To do this every fixation which occurred between 18 character positions to the left of the CWL, and 20 character positions to the right of the first letter of the CWL were identified and categorized as to location and to the type of pattern initially displayed in the CWL. Thus, boundary location was ignored. To categorize by location, the area of interest was divided into 13 regions of 3 character positions each, and each fixation was classed according to the region it fell in. With 5 CWL alternatives and 13 regions, there were 65 fixation categories. For each subject, the durations of all fixations in each category were obtained, and a mean fixation for each category obtained. Corresponding means for the 10 subjects were then averaged to yield an average fixation duration for the entire group for each category. These average values are plotted in Figure 20. With the W-Ident condition, in which no display change took place, serving as a baseline, it appears that the other CWL alternatives did have the effect of inflating fixation durations as expected. It also generally appears that the effects of these visual patterns and display changes was limited primarily to the region immediately around the CWL.

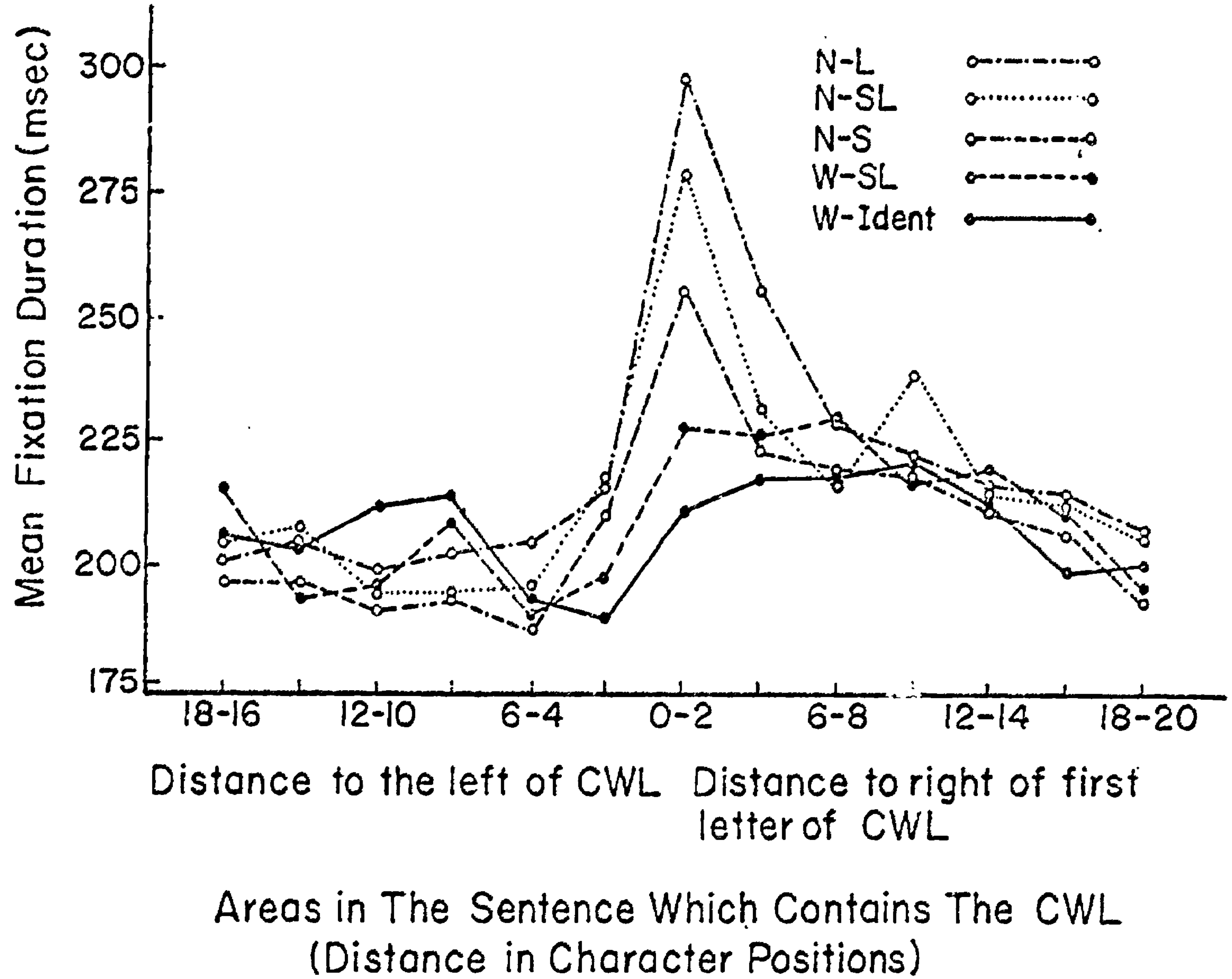


Figure 20 - Boundary Experiment: Mean duration of fixations falling in different areas on the line containing the CWL.

The Effect of Perceived Stimulus Change

The increased fixation durations may have been due to any of three causes: the effect of encountering a non-word letter string, the effect of a change in the stimulus display from one fixation to the next, or the effect of observing a display change take place directly. The latter cause would be considered an artifact in the experiment, since it was hoped that the display changes would take place early enough that subjects would not be able to directly observe them. Therefore, it was thought prudent to attempt to determine whether perceived movement might be having an effect on the data.

The first test made was to determine whether the number of letters that changed in the CWL when the display change was made affected the fixation duration. If the subjects actually saw the display change take place, a logical assumption would be that if more letters in the CWL were changed more disruption would be produced, yielding a longer fixation. The CWL initially-displayed alternatives were classed in seven categories according to the number of letters which were different between them and the corresponding Base Words. Category 1 contained instances of no difference, the W-Ident alternatives. In Category 2, 16-20% of the letters were different; in Category 3, 29-33%; category 4, 40-43%; category 5, 50-60%; category 6, 67-86%; and category 7, 100%. All CWL alternatives in category 7 were N-S lternatives.

The data analyzed included only the first fixation after a display change occurred, and then only if the fixation were centered on the CWL. Each of these fixations were categorized according to the category of the initially-displayed alternative which had existed. It was also categorized according to the location of the prior fixation, whether 1-3, 4-6, 7-9, 10-12 or 13-15 character positions prior to the CWL. This yielded a five (prior fixation location) by seven (category of CWL alternative) category scheme. For each subject, a mean fixation duration was obtained for all fixations in each of these categories, thus yielding 35 mean fixation durations. These means were then analyzed with a 3-way Analysis of Variance, with factors being category of CWL alternative, location of prior fixation, and subjects. Main effects and interactions involving the subject variable could not be tested. There was a significant effect for the location of prior fixation, which will be discussed in a later section. However, of primary interest here is the fact that category of CWL alternatives (hence number of letters that had been changed from one fixation to the next) did not have a significant effect ($F = 1.498$, $p < .20$, 6 & 54 df) nor did it interact with the location of the prior fixation ($F = 1.204$, $p < .24$, 24 & 216 df). Thus, there is no evidence that the number of letters changed had any effect on these data.

A second attempt to determine whether subjects might have seen the display change take place actually aimed at finding out whether the amount of lag in making the display change after the eye came to rest had any effect on the data. This was done by identifying all instances in which the subject fixated one particular three-character-position region prior to the display change, then fixated another particular region on the fixation following the change. These two regions were so selected that two boundary locations lay between them. Thus, for some of the instances the display change was triggered by crossing a boundary which occurred early in the saccade, and for others the change was triggered by crossing a boundary late in the saccade. Therefore, for the former instances the display change occurred earlier than for the latter. The data for these two conditions were examined to see whether this time difference produced a difference in fixation durations for the fixation immediately after the display change was made.

To carry out this analysis, all instances were identified in which the fixation just prior to the display change was located 6 to 9 character positions left of the CWL, and the fixation after the change was on the 2nd letter of the CWL. These were divided into those instances when the boundary was set three character positions prior to the CWL and those where it was set on the first character position of the CWL. A mean fixation duration score for each of these two instances was calculated for each subject. A t-test indicated that there was no significant difference between the fixation durations under the two conditions ($t = 1.19$, 9 df). Saccades launched from the area 10-12 character positions prior to the CWL and landing in the same region were also divided into those instances where the boundary was set at the same two locations. Again a t-test of the mean fixation durations failed to indicate a significant difference ($t = 1.52$, 9 df). The same procedure was repeated for saccades beginning in the same two regions, but the fixation following the display change being either on the 2nd or 3rd character positions in the CWL, thus increasing the number of fixation durations in the data. Again the t-tests were not significant. These comparisons involved 40 pairs of mean fixation durations for individual subjects. For half of them, the fixation duration was larger when the boundary was located three character positions left of the CWL, and for the other half the fixation duration was larger when the boundary was located on the first letter of the CWL. Thus, there was no evidence that the added delay in the display change produced by having the boundary just prior to the fixation location, rather than earlier in the saccade, caused any increase in the fixation durations.

Although these two tests are not adequate to rule out all possibility that subjects may have seen the display changes take place at times, and that this may have influenced the data, they do provide some evidence that the data were not being affected by such artifacts.

Effects of the CWL Stimulus Pattern and of the Display Change

This section will review the data of greatest interest, that which bears on the question of the size of the perceptual span. The three major dependent variables were duration of the last fixation prior to the stimulus change, duration of the first fixation after the change, and the number of regressions into the CWL.

Duration of the Fixation Prior to the Display Change. The durations of fixations immediately prior to the display change were examined to find out how far from the CWL there was evidence that the subject was detecting the presence of a non-word letter string in his peripheral vision. These fixations were categorized according to their location and according to the type of initially-displayed alternative present in the CWL. There were seven location categories: the first three character positions in the CWL, and 1-3, 4-6, 7-9, 10-12, 13-15 and 16-18 character positions to the left of the CWL. The five CWL alternative categories have been described earlier. Factorially combining these produced 35 categories. For each subject a mean fixation duration was calculated for the fixations in each category, and then the data for all subjects were averaged for each category. These averages are shown in Figure 21, which indicates the mean fixation duration for the fixations at different locations when different stimulus alternatives were present in the CWL. A one-way Analysis of Variance was carried out at each fixation location to determine whether the stimulus pattern in the CWL influenced the mean fixation durations in that region. Only two of these analyses found a significant effect: fixations 1-3 character positions prior to the CWL ($F = 2.62$, $p < .05$, 4 & 45 df) and fixations on the first three letters of the CWL itself ($F = 4.69$, $p < .01$, 4 & 45 df). Newman-Keuls tests (Winer, 1962) at each of these points indicated that non-word letter strings produced longer fixation durations than words, with no differences found within each of these groups.

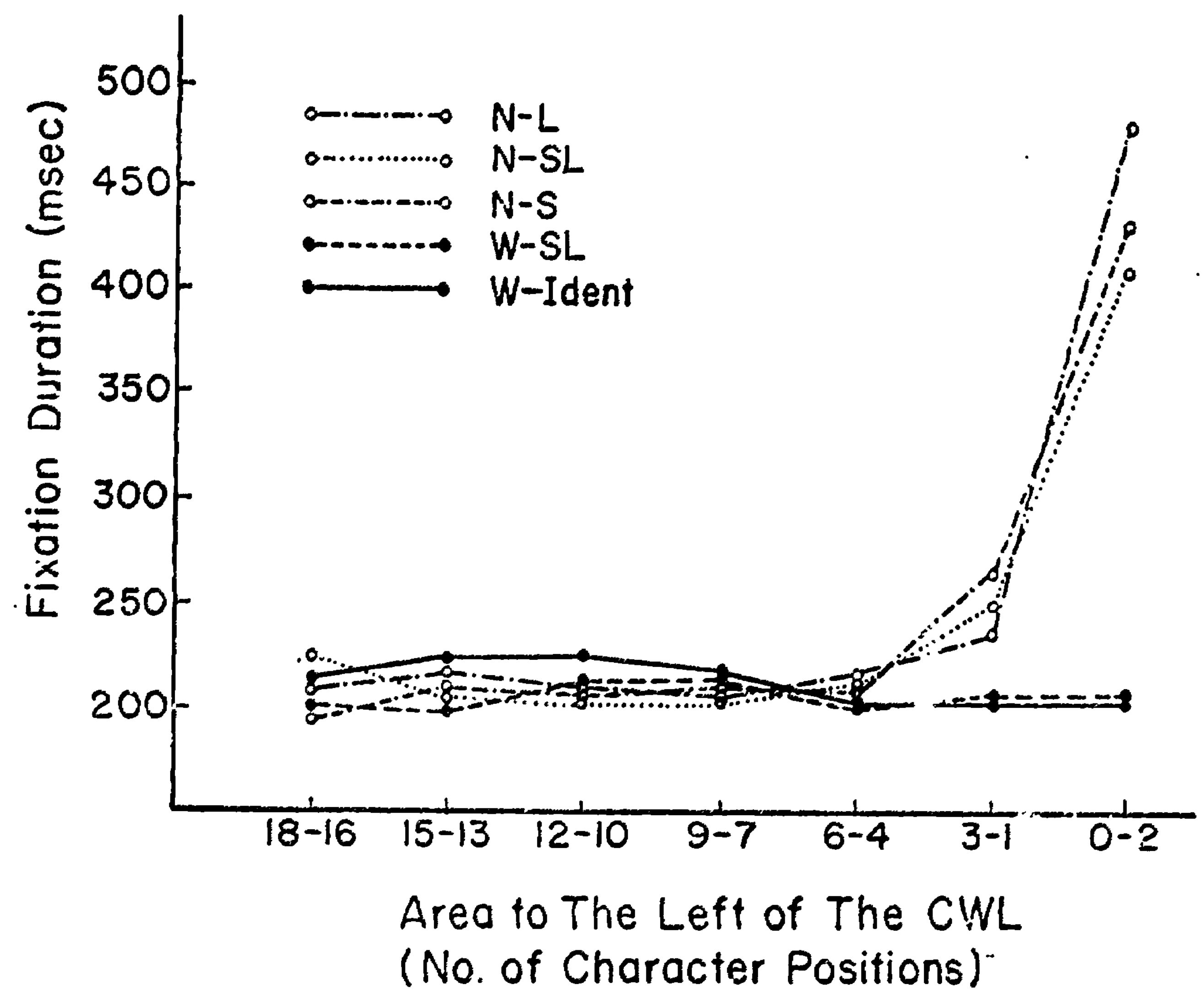


Figure 21 - Boundary Experiment: Mean duration of the last fixation prior to crossing the boundary as a function of its location and of the stimulus pattern in the CWL.

A more detailed analysis of the same type was carried out, this time with fixations being categorized as being 1-2, 3-4, or 5-6 character positions to the left of the CWL. Thus smaller location categories were used. Then t-tests were used to see if there was a significant difference between fixation durations when words and non-words occupied the CWL. The differences were significant for the 1-2 location ($t = 2.78$, $p < .05$, 9 df), and the 3-4 location ($t = 2.73$, $p < .05$, 9 df), but not for the 5-6 location ($t = .24$).

Thus the data provided no evidence that the subjects were recognizing that a particular letter string was not a word when they fixated more than 3 or 4 character positions to the left of the beginning of the string.

Duration of the fixation after the display change. The durations of the fixations which occurred immediately after the display change were analyzed to learn how far into the periphery certain visual characteristics were picked up from the CWL by the subjects. The data used for this analysis included the durations of all fixations which occurred immediately after the eye had crossed the boundary and which were located on the CWL, including the spaces to right and left.

First, these data were examined to determine whether the fixation duration was different if the fixation was directed toward the first or last half of the CWL. Fixations were categorized according to whether they were directed toward the first or last half of the CWL, and according to the type of initially-displayed alternative which had occurred at the CWL. Thus two locations and five CWL alternatives produced 10 categories. For each subject a mean fixation duration was computed for the fixations in each category. Then t-tests for correlated data were used to test for a difference in fixation duration for fixations landing on the first and last half of the CWL when each of the CWL alternatives occurred, and for the data collapsed over the CWL alternatives. The t values which resulted ranged from .10 to 1.00, none being significant. Thus it was concluded that where the fixation was located within the CWL region had no effect on its duration and that the data could be collapsed over this variable.

Next, these data were analyzed to determine how far from the CWL the subjects were picking up certain visual information from that region, particularly word shape and specific letter information. For this analysis, the fixations which occurred immediately after crossing the boundary and which were located on the CWL were categorized according to the location of the prior fixation, and according to the type of alternative which had previously been displayed in the CWL. Five prior fixation locations were used: 1-3, 4-6, 7-9, 10-12, and 13-15 character positions prior to the CWL. Very few fixations occurred at greater distances from the CWL which were followed immediately by a fixation on the CWL, so these data were ignored. The five initially displayed alternatives have previously been described. The factorial combination of five prior fixation locations and five CWL alternatives yielded 25 categories. For each subject, a mean fixation duration was calculated for each category. These data are summarized in Figure 22. They were analyzed by a three-way Analysis of Variance, with factors being prior fixation location, CWL alternative, and subjects. Significant main effects were found for both CWL alternative ($F = 9.80$, $p < .0001$, 4 & 36 df) and for prior fixation location ($F = 7.907$, $p < .0002$, 4 & 36 df). It was not possible to test main effects or interactions involving subjects. The CWL Alternative X Prior Fixation Location Interaction was not significant ($F = 1.397$, $p < .16$, 16 & 144 df). However, further investigation of this interaction was carried out. This was justified on two bases. First, we had previously planned to make comparisons among CWL alternatives for data in each prior fixation location category. Second, it was felt that the test for an interaction was a weak test for the data pattern we had anticipated. In fact, the data showed exactly the pattern anticipated, with no differences among the CWL alternative conditions when the prior fixation was farthest from the CWL, and with the data for the other CWL alternatives rising above the data for the W-Ident condition when the prior fixation was closer to the CWL. We had not, of course, anticipated exactly where the data for other conditions would begin to rise above the W-Ident condition. However, in these other respects, the data pattern was exactly as had been expected. Had we been able to test for this exact interaction pattern, rather than simply for a general interaction, the interaction would have been highly significant statistically. On these bases, then, further analyses were carried out.

The fixation duration data for each prior location fixation category were tested with a Newman-Keuls test (Winer, 1962) to determine if there were significant differences among the durations produced by the different CWL alternatives. The results of these tests are shown in Table 6, where means adjacent to the same vertical line were those which the tests indicated did not differ significantly.

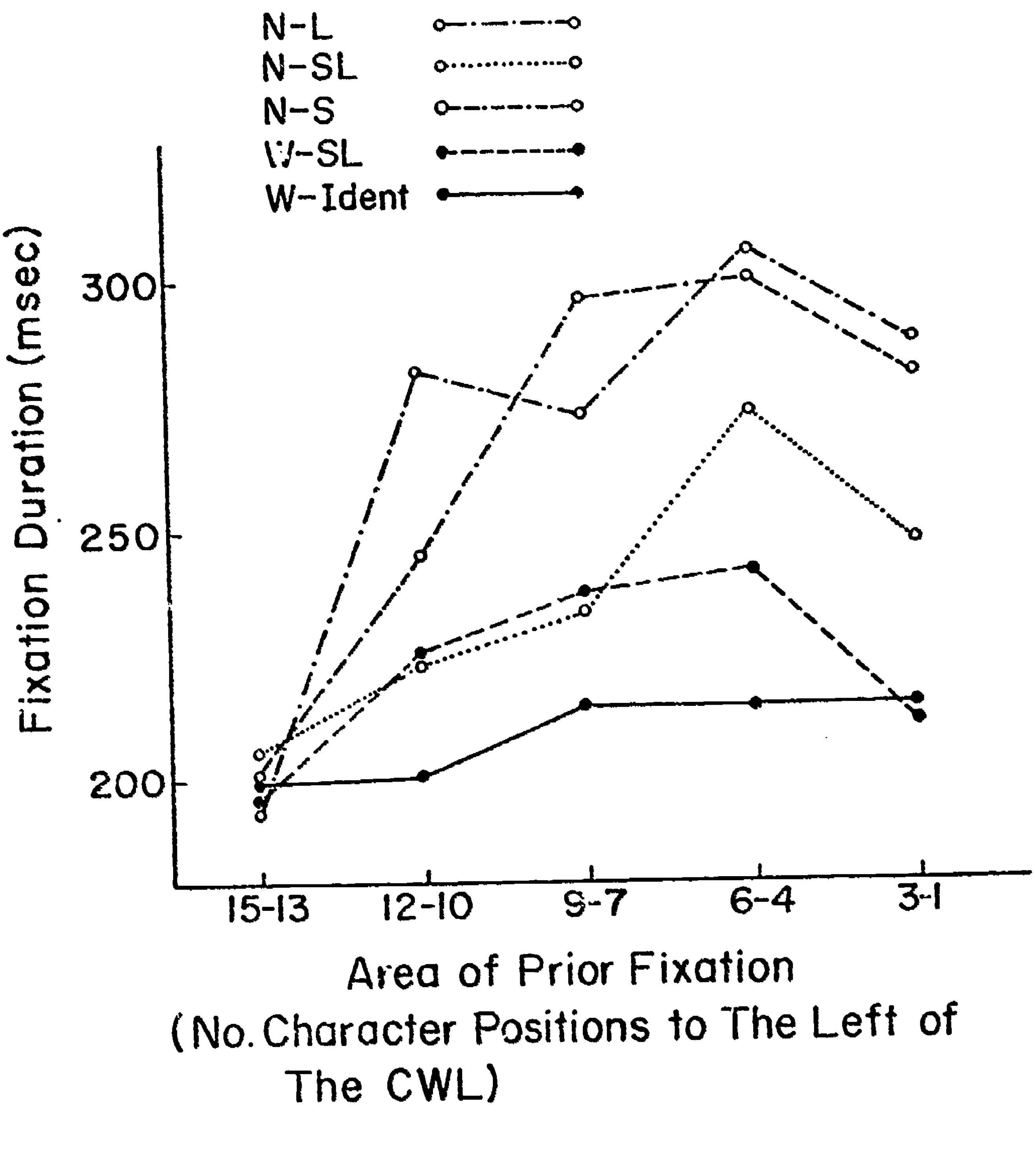


Figure 22 - Boundary Experiment: Mean durations of fixations falling on the CWL immediately after crossing the boundary as a function of the location of the prior fixation and of the initially displayed CWL alternative.

TABLE 6

BOUNDARY EXPERIMENT: MEAN DURATIONS OF FIXATIONS FALLING ON THE CWL IMMEDIATELY AFTER CROSSING THE BOUNDARY FOR DATA CATEGORIZED ACCORDING TO THE LOCATION OF THE PRIOR FIXATION AND TO THE INITIALLY DISPLAYED CWL ALTERNATIVE

Area 15-13 Cond.	Mean	Area 12-10 Cond.	Mean	Area 9-7 Cond.	Mean	Area 6-4 Cond.	Mean	Area 3-1 Cond.	Mean
N-SL	214.85	N-L	279.27	N-S	295.87	N-L	299.83	N-L	287.25
N-S	208.00	N-S	244.13	N-L	272.10	N-S	299.73	N-S	280.55
W-Id	207.18	W-SL	224.78	W-SL	236.92	N-SL	279.12	N-SL	245.50
W-SL	200.82	N-SL	221.35	N-SL	230.20	W-SL	242.55	W-Id	212.57
N-L	198.05	W-Id	202.67	W-Id	212.97	W-Id	211.10	W-SL	208.07

Note.-Lines to the right of each column indicate the results of Newman-Keuls tests. Means adjacent to a common line are not significantly different at the .05 level. Fixation durations are reported in milliseconds.

The mean fixation duration was not influenced by the different CWL alternatives when the previous fixation was 13-15 character positions from the CWL. Thus, there is no evidence that the subjects detected the change in the stimulus under these conditions, which is to say that there is no evidence that they acquired either word shape or specific letter information from the CWL when their eye was over 12 character positions to the left of that location.

When the prior fixation was 10-12 or 7-9 character positions from the CWL, the N-S and N-L alternatives led to significantly longer fixation durations than did the W-Ident alternative. Since no stimulus change took place with the W-Ident alternative, it serves as a baseline to judge the effect of the other alternatives against. Thus, it appears that when subjects were fixating between 7 and 12 character positions from the CWL, they acquired visual information both concerning the general word shape and concerning the first and last letters of the letter string in the CWL. Changing either of these caused an inflation in the fixation duration on the next fixation. However, neither the N-SL nor the W-SL alternative produced a significantly increased fixation duration in this region as compared with the W-Ident alternative. Thus, when both word shape and first and last letters were the same as those of the Base Word, the changing of internal letters failed to produce a significant increase in the fixation duration. Thus, the data failed to provide evidence that the subjects were acquiring visual information concerning specific letters within the word, other than their word shape properties, when they fixated more than 6 character positions from the CWL. However, this conclusion must be subject to further study since the fixation durations produced by the N-SL and W-SL alternatives were somewhat greater than those under the W-Ident alternative with both of these prior fixation location conditions. The difference was not statistically significant, however. It should also be noted when the prior fixation was 7 to 12 character positions to the left of the CWL there was no difference in fixation durations between the N-SL and W-SL conditions; there is no evidence here that subjects were distinguishing between words and non-word letter strings.

It is notable that when the prior fixation was 4-6 character positions prior to the CWL, the N-SL alternative produced a significantly longer fixation duration than the W-SL alternative, and both were longer than those produced by the W-Ident alternative. Thus, it appears that when the eye was within 6 character positions to the left of the CWL, information concerning internal letters in the word was being detected, and the subjects were distinguishing between whether the pattern in the CWL was a word or a non-word. This is taken as evidence that the subjects attempted to make a semantic interpretation of words beginning within six character positions to the right of their point of fixation. This conclusion is similar to that reached in the last section, where there was no evidence that the readers distinguished between words and non-word letter strings lying more than four character positions to the right of their point of fixation.

A final interesting characteristic of the data pattern was that when the prior fixation was just 1-3 character positions prior to the CWL, there was no difference in fixation durations for W-Ident and W-SL alternatives. It had been expected that the most disruptive situation to reading might be to have one word in the CWL, to have the reader fixate close enough to it to obtain a semantic interpretation of it, and then to have that word be changed to a different word for the next fixation. As it turned out, this was the condition which produced the least disruption, even though the second fixation was directly on the CWL itself. The most reasonable explanation of this data pattern seems to be that if the reader succeeded in making a semantic identification of the word in a certain location on one fixation, the visual characteristics of that region of text were completely ignored on the next fixation as he continued his reading beyond that point. Surprisingly, this appeared to be so even if the region of change was in central vision on the fixation after the change occurred. This tentative conclusion needs further investigation, of course, but if it proves to be correct will be important in understanding how the reader takes information from the visual representation of the text for use in his reading processes.

In conclusion, these data suggest that neither word shape nor specific letter information was being acquired by the subjects from words beginning more than 12 character positions to the right of the fixation point. Visual characteristics of internal letters in a word appeared to be acquired for words beginning no more than 6 character positions to the right of the fixation point. There was no evidence that a semantic interpretation was being made for words beginning more than 6 character positions to the right of the fixation point. Finally, it was suggested that once a word had been identified, no further visual information was taken from that region of text, even if the stimulus in that region was changed for the next fixation and the fixation was directly on that region.

Regressions. Several types of analyses were carried out on regressions which brought the eye back into the regions of the CWL. For the most part, these were quite uninformative. There was some evidence that if the boundary was set at the first or fourth letter of the CWL itself, thus providing the reader with the opportunity to fully see the CWL alternative prior to crossing the boundary, there were more regressions into the CWL if the CWL alternative was a non-word than if it was a word. The average number of regressions per subjects into the CWL under these conditions, out of a possible 18, were as follows: W-Ident, 2.90; W-SL, 2.65; N-SL, 4.05; N-L, 4.05; N-S, 4.10. The durations of these fixations was not affected by the CWL alternative. Again it should be noted that when the change produced was from one word to another word, and the eye was close enough to the CWL on the fixation prior to the change to permit making a semantic interpretation of the word initially appearing in the CWL, there was no evidence that the change to a new word was even detected. That is, there were no more regressions back to the CWL when the initially displayed alternative was a W-SL than when it was a W-Ident.

The Effect of Grammatical Category of the CWL

Several analyses were carried out to determine whether the grammatical category of the Base Word in the CWL had any effect on how far into the periphery information from that region was acquired.

Duration of the fixation prior to the display change. Fixations immediately preceding the display change were categorized according to location (first three character positions of the CWL, or 1-3, 4-6, 7-9, 10-12 or 13-15 character positions prior to the CWL), grammatical category of the CWL (subject, verb or object) and whether the CWL contained a word or non-word. This yielded a 6 X 3 X 2 category system, for a total of 36 categories. For each subject a mean fixation duration was calculated for each category. These data were then combined across subjects to yield a single mean fixation duration for each category. The results are shown in Figure 23. A three-way Analysis of Variance was carried out for the data for fixations occurring in each of the six regions separately. Factors in each analysis were grammatical category, word vs. non-word, and subjects. For fixations located 1-3 character positions from the CWL, significant effects for grammatical category and for the Grammatical Category X Word vs. Non-word Interaction indicated that a non-word in the CWL inflated the fixation durations when the CWL occupied the position of verb or object, but not when it occupied the position of the subject. No significant effects were found when the eye was further from the CWL. When the fixation was directly on one of the first three letters of the CWL, fixation durations were greater for non-words than for words, regardless of the grammatical category. Thus, there was evidence that the distinction between words and non-words was made when the eye was further from the verb or object than from the subject. Apparently this distinction was not made for the subject unless it was being directly fix-

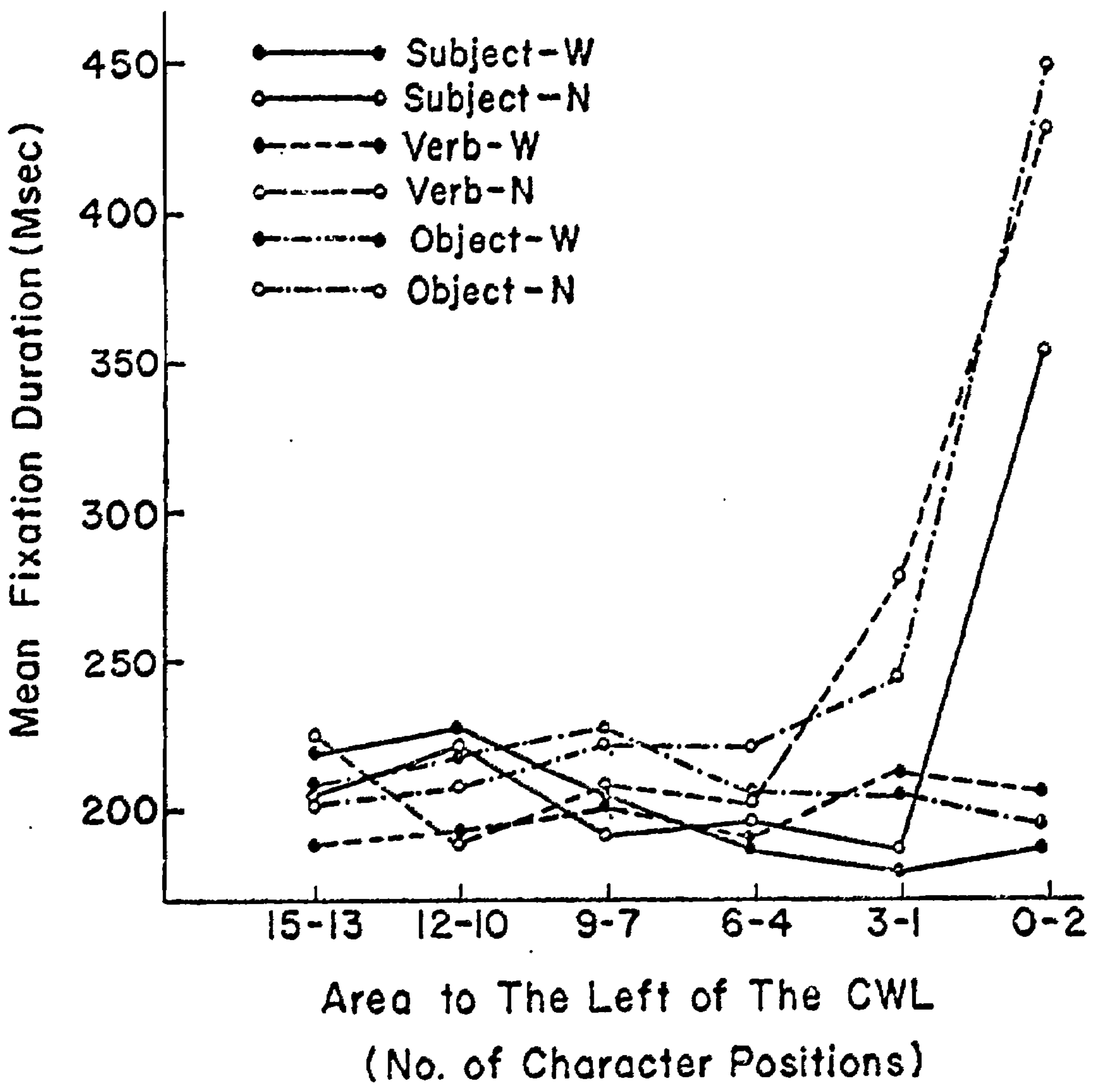


Figure 23 - Boundary Experiment: Mean duration of the last fixation prior to crossing the boundary as a function of its location, grammatical category of the CWL, and whether the initially-displayed alternative was a word or a non-word letter string.

ated. An interpretation of this finding will be delayed until the next section.

Duration of the fixation after the display change. An analysis of the data on the duration of fixations immediately after the display change also provided evidence that visual information from the CWL was being acquired less far into the periphery when the CWL occupied the position as subject of the sentence. For this analysis, the only data used were from the fixation immediately after the display change occurred, and then only if a non-word had initially occurred in the CWL and if the fixation after the display change was on the CWL. These fixations were categorized according to the location of the prior fixation (1-3, 4-6, 7-9, 10-12 or 13-15 character positions prior to the CWL) and according to the grammatical category occupied by the CWL (subject, verb or object). For each subject a mean fixation duration was calculated for each of the resulting 15 categories. These means were then entered into a three-way Analysis of Variance, with factors being prior fixation location, grammatical category, and subjects. The two testable main effects were significant, the effects due to location of prior fixation ($F = 2.88$, $p < .05$, 4 & 36 df) and to grammatical category of the CWL ($F = 3.55$, $p < .05$, 2 & 18 df). The interaction between these variables was not significant ($F = 1.37$, $p < .22$, 8 & 72 df). Mean fixation durations according to grammatical category were as follows: subject, 236 msec.; verb, 264 msec.; object, 260 msec. The display change caused less inflation of fixation durations when the CWL served as subject of the sentence than when it served as verb or object. These data are shown in Figure 24. Here it can be seen that, in agreement with the data presented in the last section, when the reader fixated just left of the CWL, he was less likely to acquire visual information from the CWL region when it served the function of subject than when it served as verb or object. Interestingly, this was not true when he fixated further to the left of the CWL, between 7 and 12 character positions. This difference only occurred when the eye was within 6 character positions of that location.

In carrying out this analysis it was also noticed that there were substantial differences in the number of fixations found in the various categories used. These data are shown in Figure 25. When the CWL was in the subject location, there were fewer than normal fixations in the region 1-6 character positions to the left of the CWL. When the CWL was in the verb location, there were fewer than normal fixations in the region 10-15 character positions prior to the CWL. A three-way Analysis of Variance on the number of fixations occurring in each category yielded a significant Grammatical Category X Prior Location Interaction ($F = 11.54$, $p < .0001$, 8 & 72 df).

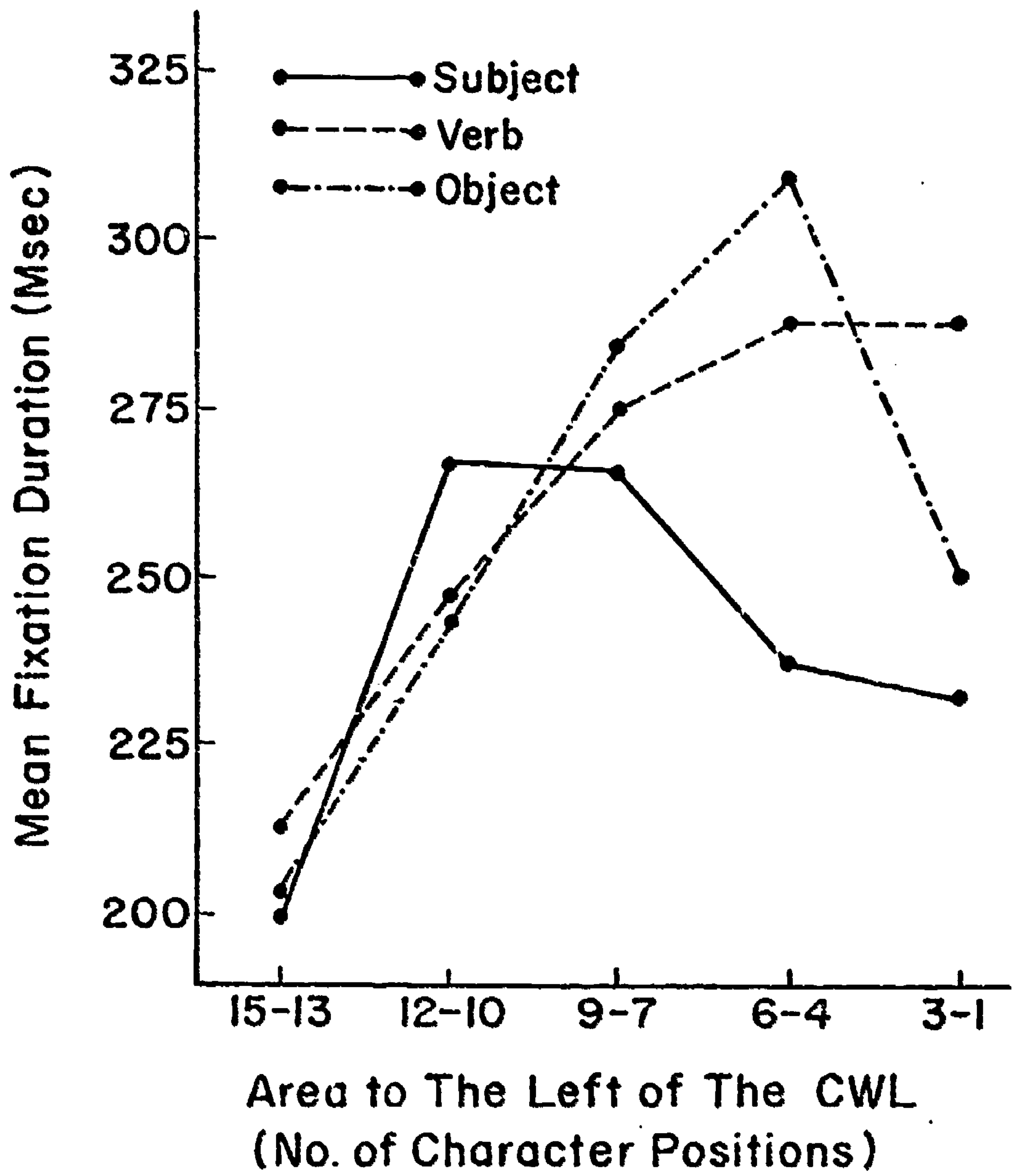


Figure 24 - Boundary Experiment: Mean durations of fixations falling on the CWL immediately after crossing the boundary as a function of grammatical category of the CWL and of the location of the prior fixation, when the initially displayed CWL alternative was a non-word letter string.

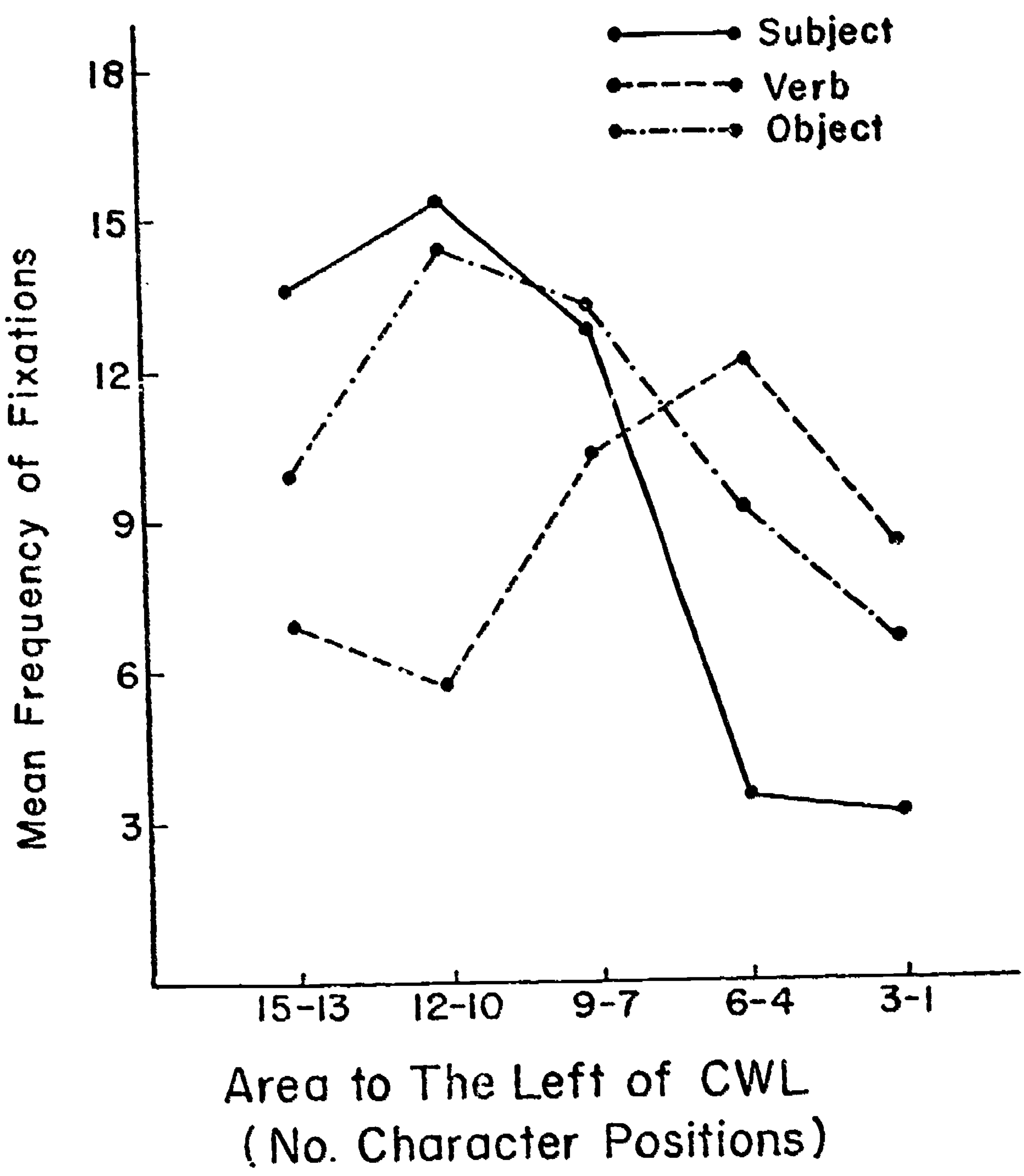


Figure 25 - Boundary Experiment: Effect of grammatical category of the CWL on the number of fixations which fall in different areas to the left of the CWL.

The same pattern was present in the W-Ident and W-SL data.

The basis of this data pattern can be seen in Figure 26, which shows the number of fixations occurring at each region of the sentence when the CWL occupied the position as subject, as verb and as object. This figure also shows the durations of fixations at each area of the sentence under the same conditions. The hatched lines between the two bar graphs indicate the three sets of five regions from which fixations were considered, depending on whether the CWL occupied the position of subject, verb or object. The bars are coded according to whether the data came from conditions when the CWL was subject, verb or object. Bars with lines sloping down to the right indicate data from paragraphs in which the CWL served as subject; bars with no lines indicate data from paragraphs in which the CWL served as verb; and bars with lines sloping up to the right indicate data from paragraphs in which the CWL served as object. From this figure it can be seen that the differences observed in number of fixations in different categories, shown in Figure 25, was due to a general tendency for subjects to make fewer fixations in the region occupied by the terminal character and period from the prior sentence, the spaces between the sentences, and the article at the beginning of the sentence containing the CWL. It can also be seen that when the subject did fixate in that region, the duration of his fixation tended to be substantially shorter than usual.

Thus, it appears that subjects tend to avoid fixating the region between sentences, and that when they do fixate there, their fixations tend to be shorter than normal. It also appears that when they fixate in this region, they tend not to acquire visual information from words as far into the periphery as they do at other regions in the sentence. This seems to account for the data patterns reported in this section. There seems to be no other effect specifically due to grammatical category itself, either on fixation durations or on the size of the perceptual span.

One final feature of the data which was noted was a tendency for subjects to fixate the left and right half of the CWL equally frequently when it served the function of subject, but for the left half to receive more fixations when it served as verb or object. These data are shown in Figure 27, which indicates that for verb and object nearly 75% of all fixations on the CWL were on the left half of the word. A three-way Analysis of Variance (3 grammatical categories x 2 fixation locations x 10 subjects) found significant effects for fixation location ($F = 20.53$, $p < .002$, 1 & 9 df) and for the Fixation Location X Grammatical Category Interaction ($F = 20.29$, $p < .001$, 2 & 18 df). This may reflect a tendency

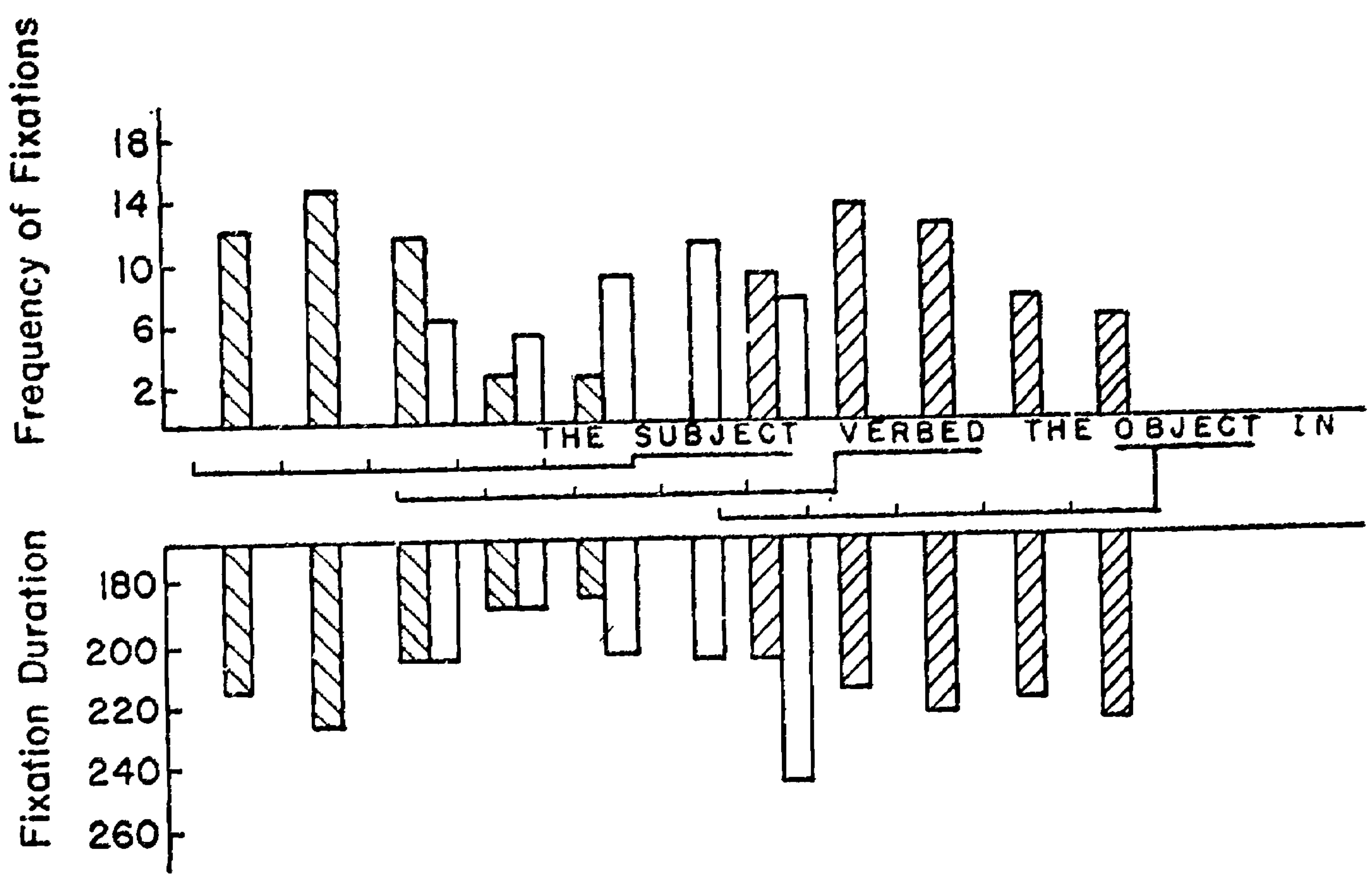


Figure 26 - Boundary Experiment: Effect of location in text on the frequency and duration of fixations. The frequency and duration of fixations occuring up to 15 character positions prior to the CWL are shown in relationship to the area of text they fell in when the CWL was subject, verb or object.

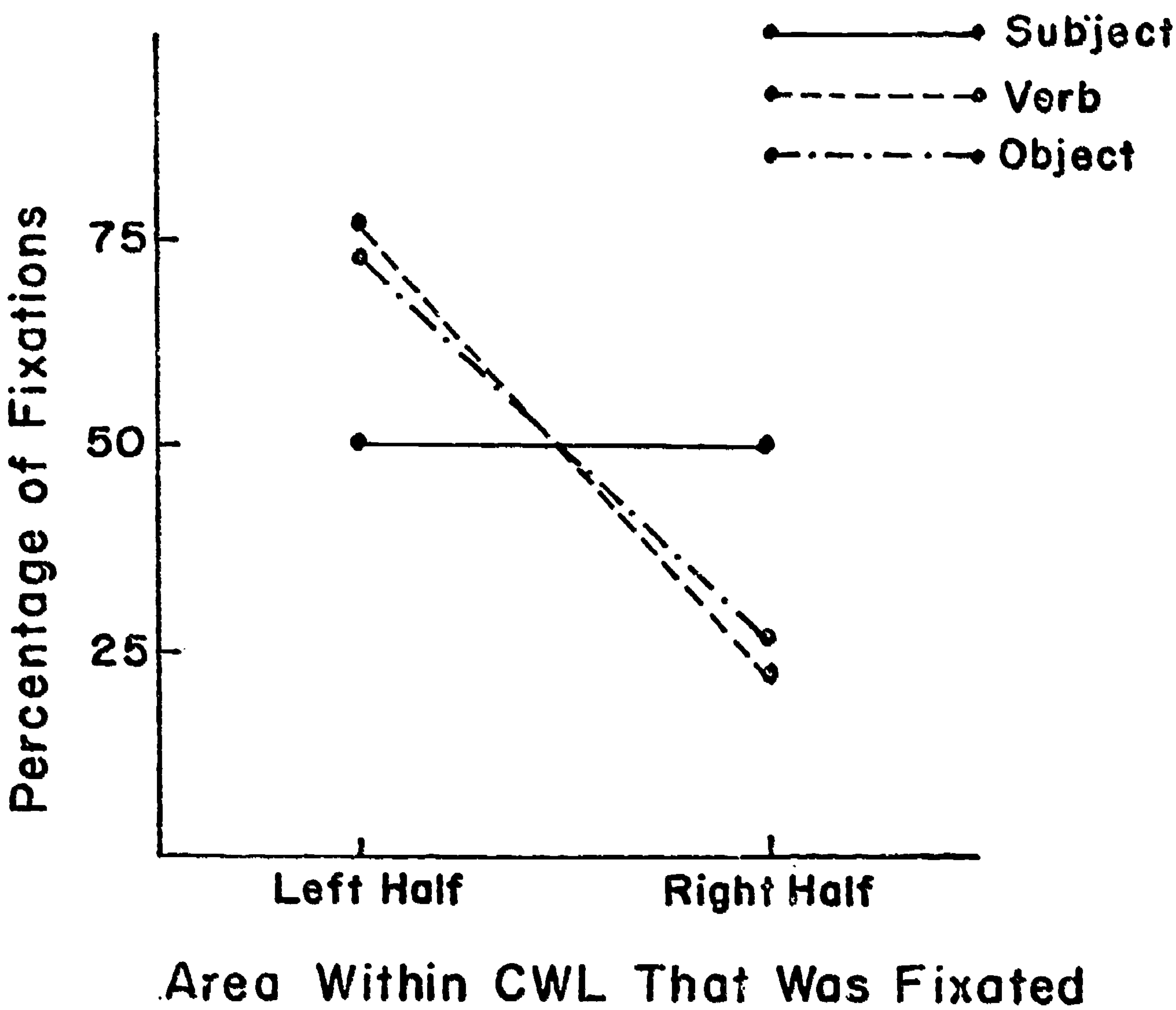


Figure 27 - Boundary Experiment: Percentage of fixations on the left and right half of the CWL as a function of grammatical category of the CWL.

for fixations to be more accurately located on the verb or object than on the subject in sentences of the syntactic construction used here, since saccades coming to the subject region originated either some distance from their target (at some location in the previous sentence) or from a nearer region (between the sentences) at which they tended not to acquire peripheral visual information.

It is of interest that when the reader fixated in the region 1-6 character positions prior to the subject position he failed to obtain peripheral visual information. This suggests that fixations made in the region between sentences play a special function. There are two possible explanations of the type of cognitive processes that might be occurring during these fixations, each of which would be harmonious with the notion that they are not used primarily for obtaining additional visual information for reading. The first possibility is that, as Woodworth (1938) has suggested, the understanding of the text lags somewhat behind the visual impressions. This may make it necessary occasionally to pause for an extra fixation at the end of a sentence to permit processing of the information obtained to be complete. The purpose of this fixation, then, would not be for visual input, which may account for its reduced duration.

A second possible explanation is that there is a certain amount of inaccuracy in the guidance of eye movements. Readers are capable of identifying regions in the text where there are no letters and are generally able to avoid them, as shown by Abrams and Zuber (1972). These investigators presented subjects with text modified to have a series of blank regions between words at random locations. They found that subjects made few fixations within these blank regions. Thus, it would seem likely that subjects identify the region between sentences, containing a punctuation mark and two spaces, and attempt to avoid locating fixations in these regions. However, oculomotor control is not complete, and the eye may inadvertently fall on this region. When this occurs, the reader quickly recognizes that he is fixating a region of little visual information, and the next saccade is initiated. Thus, the fixation is shorter than normal and the subject does no processing of peripheral visual information.

Which of these possibilities accurately account for the type of cognitive processing taking place during fixations between sentences must be the subject of additional research.

Regressions. Neither the number of regressions into the CWL, nor the duration of fixations in these regressions was influenced by the grammatical category of the CWL.

Effect of Word Length of the CWL

Since the CWL was either 5, 6 or 7 letters in length, the data were analyzed to learn whether the length of the CWL had any effect on the dependent variables. Several Analyses of Variance found no significant effects of word length on the duration of fixations prior to the stimulus change or on the number of regressions or the duration of fixations in those regressions. However, the length of the CWL did have an influence on the duration of fixations immediately following the display change. For this analysis only the first fixation after the display change occurred was considered, and then only if it fell on the CWL and if the CWL had previously contained a non-word letter string. The fixations were categorized according to the location of the prior fixation and the length of the CWL. With five prior fixation locations and three word lengths there were a total of 15 categories. A mean fixation duration was calculated for each category for each subject, and then from these means a mean fixation duration was calculated for each category across subjects. These data are shown in Figure 28. A three-way Analysis of Variance (5 prior fixation areas by 3 word lengths by 10 subjects) found significant main effects for word length ($F = 7.52$, $p < .005$, 2 & 18 df) and for prior fixation location ($F = 3.75$, $p < .01$, 4 & 36 df). The interaction was not significant ($F = .55$). Fixation durations for different word lengths were: 5 letters, 233 msec.; 6 letters, 261 msec.; 7 letters, 262 msec. Thus, changes in the visual pattern in the CWL produced longer fixation durations when it was 6 or 7 letters in length than when it was 5 letters.

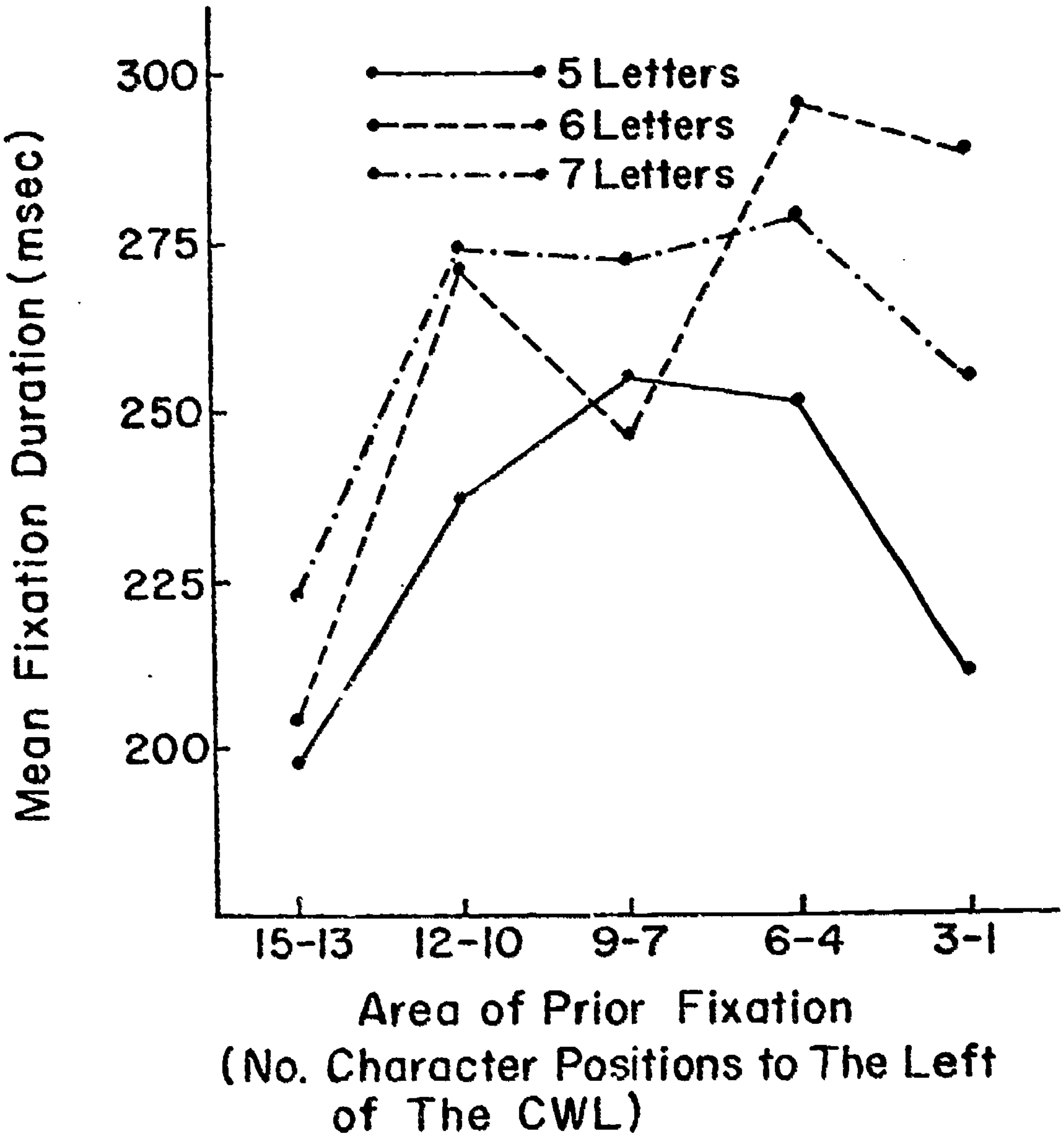


Figure 28 - Boundary Experiment: Mean durations of fixations falling on the CWL as a function of length of the stimulus in the CWL and location of the prior fixation.

CHAPTER 10

DISCUSSIONS AND CONCLUSIONS

The results of the five experiments carried out in this series have implications for several questions about the nature of skilled reading including those discussed in the first chapter. These questions will now be discussed.

From What Region is Visual Information Acquired During a Fixation?

The studies reported here make it clear that different aspects of the stimulus display are acquired by the reader different distances from the point of central vision. Thus there is no single perceptual span in reading. The particular aspects of the text stimulus investigated in the present study were word length, exterior word shape, and specific letters, particularly initial and final letters in the word.

Word length pattern appeared to be detected furthest into the periphery, at least 12 character positions from central vision and perhaps as much as 15 or more. Removing this aspect of text from the display in peripheral visual areas had the effect of reducing saccade length, particularly reducing the number of long saccades.

The Window Experiments and the Boundary Experiment yielded quite similar estimates of the distance into the periphery that word shape and specific letter information is acquired, and both indicated that word shape is obtained no farther out than is specific letter information. The Window Experiments yielded data suggesting that readers need specific letter information no further than 10 or 11 character positions to the right of central vision. The Boundary Experiment indicated that subjects were picking up such information from words beginning 10 to 12 character positions from central vision, but not from words beginning 13 to 15 character positions away. Thus, this study yielded an estimate of about 12 or 13 character positions as being the limit for acquiring word shape and specific letter information. The general agreement of the two studies produces increased confidence in their results.

The Boundary Experiment also produced evidence that the distinction between words and non-words, and the semantic interpretation of words was being made for words beginning no further than 5 or 6 character positions to the right of central vision. Since these words ranged in length from 5 to 7 letters, it appears that word meanings are identified only for words that lie almost completely within the region in which word shape and letter information are acquired, 12 to 13 character positions into the periphery.

Results of another of the studies clearly indicated that the region from which visual information is acquired during a fixation is not symmetric. No detrimental effects were observed when the region of full visual information was reduced to only 4 character positions to the left of the central vision, if full information were available some distance to the right (in this case, 20 character positions). There was some evidence from the Boundary Experiment that the region to the left of central vision from which useful visual information is acquired may be even less than that at times.

At present, then, it appears that word identification is being carried out in a visual region extending from no more than four character positions to the left of central vision to no more than 12 or 13 positions to the right, a region of no more than 16 to 18 character positions and perhaps even less. Thus, reading tends to be carried out in a relatively small visual region, primarily in the left half of the retina, for skilled English readers.

The question of whether useful visual information is acquired from other lines than the one being fixated remains an open question at this time, in need of further research. The experiment conducted on this question found that reading was facilitated when the window included the line below the fixated line as well as the line being directly read. However, it is not clear whether this was due to the actual acquisition of useful information or was due to some artifact produced by the use of the window technique. The research of Willows and MacKinnon (1973) and Neisser (1969), indicating that readers occasionally pick up information from words and phrases presented between the lines of text, suggests that this question is worthy of further research.

Another question relating to the perceptual span is whether the region from which various sorts of visual information are acquired is the same on every fixation, or whether it varies from time to time in the text, or whether the subject is able to vary it at will. This question relates to another question raised in an earlier chapter: did reading under the window conditions cause the readers to narrow their span of attention, so the results of those studies were not typical of normal reading? If this were so, the Window Experiments could have greatly underestimated the size of the region from which the subjects normally acquire visual information during a fixation as they read. The results of the Boundary Experiment clearly indicate that this was not the case. As the subjects read the paragraphs in the Boundary Experiment, there was only one point during each paragraph where a stimulus change might take place. Twenty percent of the time (when the W-Ident condition occurred) no display change took place at all. At other times the change often took place so far into the periphery that it was apparently undetected. Thus, the display changes were of such a nature that there is no reason why such a narrowing of the attention span should have been produced in that study. In addition, the subjects used in that study had never read under window conditions, so the experimental situation itself had not come to elicit a narrowing of the attention span. It is notable, then, that the data obtained in the Boundary Experiment led to conclusions very similar to those from the Window Experiments. There is no evidence that reading under window conditions caused the span to be substantially restricted in size.

The Window Experiment in which the window was shifted to left and right, placing the window region primarily to left or right of central vision, might be viewed as an attempt to see whether the subjects were able to read equally well when being forced to obtain information from different areas of their retina. Whether the window was shifted left or right, the reader still had the same size region of normal text information available, and in both conditions a normal text pattern was present in the central foveal region (normal text was always present 1^{o} to left and right of central vision). Still, reading was disrupted when the window extended primarily to the left, but not when it extended primarily to the right. Thus, there was a limit to the ability of the readers to select information from one retinal region rather than another for their reading. Whether less extreme adjustments can be made, and how much practice is required to do so, remains a question for further study.

There is still the question of whether, from fixation to fixation, there are differences in the area from which visual information is acquired. For instance, when the reader makes the first fixation on a new line does he tend to cast his visual attention more to the left of the fixation point, whereas on succeeding fixations does he concentrate more on information to be right? There are two aspects of the data which suggested that some changes might be occurring, though neither is conclusive. First, as mentioned earlier, there is some evidence that when a word occurred in the CWL and the reader fixated near enough to it to read it, and then on the next fixation he looked directly at the CWL, in which there was now a different word, he failed to note the change. Thus he appeared to be ignoring the visual pattern in central vision on that fixation.

A second bit of data on this question also comes from the Boundary Experiment. It was found that when subjects fixated the region between sentences they did not appear to acquire visual information as far into the periphery as they did when they fixated other areas of the sentences. Of course, the information must have been registered on the retina, and present in an internal visual representation, but it apparently was simply not used in the reading process.

Thus, it appears that the specific region from which visual information is used in reading may not be identical from fixation to fixation. The results concerning the size of the perceptual span reported earlier may indicate the general region within which the reader is capable of obtaining useful information. Just what information he takes from that region may vary from fixation to fixation, according to his momentary needs in reading. If so, this calls for a very detailed extension of the present research to investigate this phenomenon farther.

Is Detailed Eye Guidance Carried Out During Reading?

As indicated in Chapter 1, theories of eye behavior control in reading range from assuming almost totally random control to assuming that on each fixation the eye is cast to that specific area which is believed to contain the most informative information for the purpose of testing the reader's present hypothesis concerning the meaning of the text. Of course, the random control hypothesis can only be challenged by identifying non-random patterns in eye behavior data. Some evidence for non-random eye control, taken from the research of others, was reviewed in Chapter 1. Certain data from the present studies also challenge the random eye control position.

Though not conclusive, the fact that eliminating word length patterns in peripheral vision reduces saccade lengths is compatible with the notion that word length pattern information is used in guiding the eye. Also, an analysis was carried out with some of the data from the Boundary Experiment to determine whether the probability of fixating a letter in a word was a function of the length of the word. Unlike previous analyses carried out by Woodworth (1938) a definite relationship was found. The probability of fixating a letter in a one or two letter word was .107. This value rose with word length to a maximum for six-letter words, where the probability was .141. The value then dropped with added length to .112 for words 12 letters in length. As indicated earlier, fewer fixations than normal were found in the region between sentences. The probability of fixating the character position containing a punctuation mark, whether period, comma or semicolon, was .062, and the probability of fixating the spaces between sentences was .072. Thus, it appears that fixation locations are not distributed randomly throughout the text.

Assuming that fixation locations are related to the word length pattern, there are several types of explanations for why this might be so. On the one hand, it might be that the eye is being guided by linguistic aspects of the text. Word length patterns are related to the syntactic structure of text. We have shown this in pilot studies in which a mutilated version of a passage was prepared by replacing each letter in the text with an x, while maintaining capitalization, spaces between words, and punctuation. This pattern was given to subjects, who were asked to mark the locations where phrase boundaries occurred in the original text. Subjects were able to do this task with an accuracy far above chance level. Thus, word length patterns alone can be a strong cue to certain aspects of the syntactic structure. It is possible that the eye may be guided to some degree on a linguistic basis, using word length patterns as an important cue.

Another possible explanation for the relationship between word length and the probability of fixating a letter in the word is based on quite different assumptions. It is assumed that the reader obtains visual information and identifies words as far to the right of his fixation point as he is able. He then typically casts his eye a certain distance determined by how far he has been able to make word identifications. Suppose that either of two words might begin at a certain character position some distance to the right of the fixation point, one a three-letter word and the other a six-letter word. It would be more likely that enough of the three-letter word would lie within the retinal region of letter identification, thus permitting identification of the word, than that enough of the six-letter word would lie within that region. Thus there would be a greater likelihood that the six-letter word would need to be directly fixated on the next fixation than that the shorter word would need to be. On the other hand, if two other alternative patterns could lie in the same eleven-letter region to the right of the fixation point, one an eleven-letter word, and the other a combination of two five-letter words (with a space between), it is more likely that enough of the longer word would lie within the region of letter identification so it could be identified, than that enough of the second of the two shorter words would lie in that region. Thus, it would be more likely that the next fixation would need to be sent to the latter half of this eleven-letter region if it contained the second of two shorter words than if it contained the latter half of a longer word. Thus it may be that these types of assumptions could lead to the type of data pattern which we have observed, with a curvilinear relation between word length and the probability of fixating a letter in the word.

Though further research is needed to investigate the basis of this curvilinear relationship, for the present it can still be accepted as evidence against a random eye behavior control position.

One other finding which argues for eye guidance of some non-random sort is the frequency of fixating the first and last half of the CWL. The two halves of the CWL are equally often fixated when that location is occupied by the subject of the sentence. However, if the verb or object of the sentence lie in the CWL, 75% of the fixations are directed at the first half of that word location, with only 25% falling on the second half.

The Boundary Experiment also provided data that the durations of fixations are being controlled on some bases other than random control. The fact that irregularities in the text, or changes in the text pattern, inflated the fixation durations provides evidence that the fixation durations are at least to some degree reflective of the cognitive processing occurring during the fixation. Also, the fact that the durations of fixations falling between sentences were shorter than fixations in other locations in the text stands as evidence against random control of fixation durations.

A theory of reading which makes the assumption that the eye is being directed in a non-random manner from fixation to fixation and that the durations of fixations are being controlled by the cognitive activities taking place during the fixation itself is making a strong implicit assumption concerning lag in processing. That is, it is assuming that the visual information obtained during a fixation is being processed sufficiently rapidly during that fixation that decisions can be made from the information acquired concerning the termination of the fixation and the region where the next fixation should be located. For instance, if it is to be assumed that the eye is directed to certain locations based on the meaning of the sentence which one has acquired up to the present point, it must be assumed that the visual information from the present fixation has been processed sufficiently to lead to a semantic interpretation of that information and to have it integrated with the meaning obtained on prior fixations. In fact, this must have been accomplished some time prior to the end of the fixation, since the decisions to end the fixation and where to send the eye must have been made some amount of time prior to the initiation of the saccadic movement. This seems like a rather demanding requirement to place on the perceptual system, given the fact that the average fixation duration is generally

250 msec. or less, and that there is some degree of suppression of the visual input during the early part of the fixation. Some reading theorists have rejected the notion of detailed control of eye movements during reading largely on the basis that there is not enough time during the fixation to carry out the processing necessary to produce such control (for instance, Kolers, 1974). Thus, the question of processing lag, or how long it takes to process information obtained on a fixation to particular levels of identification and integration of meaning, becomes a critical question for the issue of eye guidance in reading.

The Boundary Experiment again provides some data concerning this question of processing lag. It indicates that the duration of a fixation is inflated when the reader first comes in contact with a non-word letter string. Thus, it appears that the reader processes the signal sufficiently during the fixation on which it is acquired to identify the presence of nonwords. It also indicates that under certain circumstances the presence of a change in the stimulus pattern from the prior fixation to the present fixation can produce an inflation in the duration of the present fixation. Thus, the type of processing involved in integrating the images across fixations must take place during the fixation in which information is acquired. Finally, the fact that fixations are not randomly located in the text, but rather that they are a function of word length is some indication of additional processing during fixations which is sufficient to guide the eye in a non-random manner. However, none of this is evidence for higher levels of processing during a fixation, for instance to the level of integrating the meaning of the presently-perceived region with prior meaning.

A series of studies which bears further on this question has been conducted by Isakson (1974). He made the assumption that the reader processes the meaning of a sentence as he encounters the words in reading, and that this processing consists of identifying the phrase groupings and the verb and of identifying the case relations of the various noun phrases. Thus, the semantic structure of the representation of the meaning of a sentence is assumed to consist of the meanings of the verb and of the various noun phrases with case relationships marked. From this position, he then hypothesized that meaning integration might be occurring throughout the sentence, whenever the case role of a noun phrase is identified. He assumed that the cognitive processes required to carry out this meaning integration would place a heavier-than-normal load on the cognitive processing system at the points which this activity was carried out.

In order to test these assumptions, he constructed pairs of 13-word sentences having identical words in the first eight word locations, except for the fifth word. At that location, either one of two function words could occur, one of which made the case structure of the preceding word string clear, and the other left the case structure ambiguous. He hypothesized that when the case structure was identifiable at that point, meaning integration (which he called Partial Sentence Meaning Processing, or PSMP) would be carried out, which would increase cognitive load for a short time. He further hypothesized that this increased cognitive load would be reflected in a slower reaction time to a click sounded at that point during the presentation of the sentence.

An example of the sentence pairs Isakson used in his study is:

Type A: The serene mother comforted <u>the</u> children who trusted her when they were afraid.

Type B: The serene mother comforted <u>by</u> children who trusted her grew braver every minute.

As can be seen, a Type A sentence, by including the word <u>the</u> at the fifth word location, permits the identification of the preceding text as the actor and main verb of the sentence. The Type B sentence, which has the word <u>by</u> at the fifth word location, leaves the case structure of the first four words ambiguous. Thus Isakson predicted that a click sounded during the fifth word would result in a longer reaction time for the Type A sentence than for the Type B sentence. It should be noted that practically any other basis would make the opposite prediction. Certainly there is no reason why a reaction time to a click presented during the word <u>the</u> alone should be longer than during the word <u>by</u>. If anything, the word <u>by</u> would be expected to be more complex. Also, in the Type B sentence once the word <u>by</u> is encountered it is clear that the sentence construction is going to be more complex than a Type A sentence. Thus on the basis of syntactic complexity, one might expect a longer reaction time to the Type B sentence. However, over a series of four studies Isakson found a consistently longer reaction time to a click sounded during the presentation of the fifth word when the sentence was a Type A sentence than when it was Type B, as he had predicted.

In this study, the sentences were presented visually, one word at a time, with a new word every 355 msec. Of interest here is the fact that when the click was sounded only 60 msec. after the onset of the word, a reliable difference was found between the reaction time to the Type A and Type B sentences. It is not known, of course, just how long after the click was sounded there was interference between the cognitive activity required to set up a motor response in reaction to the click, and the cognitive activity involved in determining case relationships and integrating the meaning of the sentence up to that point, but it seems clear that this was taking place within the period of time normally occupied by a fixation in reading. Thus, though Isakson's study did not involve a normal reading task, it does provide evidence that meaning integration takes place at various points throughout the sentence and that this integration can take place very rapidly once the necessary information is encountered, perhaps within the period of time normally taken by a fixation. Thus it appears possible that sufficient processing may take place during a fixation to permit the directing of eye behavior on the basis of the meaning of the text to that point. Clearly, further research is needed on this question as well.

In conclusion, there is strong evidence that the eye is being directed in a non-random manner during reading, both in terms of the locations of fixations and of the durations of fixations. There are several reasonable alternatives for eye position guidance, suggesting that guidance may be based on purely perceptual aspects, such as how far into the periphery word identification has succeeded, syntactic aspects, such as basing eye guidance on the syntactic structure of the text, or even semantic aspects, related to the meaning structure of the text or the type of information being sought from it. Exploring these alternatives should be a fruitful area for future research. Fixation duration seems to be influenced rather sensitively by the cognitive activity being carried out at a given point in the text. However, the basis for this aspect of eye guidance is not presently known, either.

Is Peripheral Visual Information being Used for Other Purposes than Eye Guidance?

In Chapter 1 it was suggested that visual information from the peripheral retinal areas might be used to facilitate reading in ways other than for eye guidance. Two specific suggestions were made: first, words may be identified on the basis of less than complete visual information; and second, certain information might be obtained about a word which is too far into the periphery to be identified. That information might reduce the amount of information which must then be acquired about the word for its identification on the next fixation. The data from the experiments are directed less toward these questions than they are toward the earlier questions, but some comments are appropriate about them.

When the research was being planned, we suspected that the reader probably has access to general external word shape characteristics of a word further into the periphery than the region where he can obtain specific information needed to identify letters. The data both from the Window Experiments and from the Boundary Experiment failed to support this. It appears that specific letter information, particularly for letters at the beginning and end of the word, is available as far into the periphery as is general word shape information. Thus, it is probably not true that words are sometimes identified far enough into the periphery that specific letter information is not available, with identification being based specifically on the external word shape alone. On the other hand, the present study provided little evidence concerning what aspects of the visual stimulus were being used to identify words at various regions in the retina. Providing accurate word shape information 6 to 8 character positions from central vision did facilitate reading over the condition in which inaccurate word shape was presented, so general word shape does appear to be useful to the reader. It is possible that at times words most centrally fixated are identified strictly on the basis of external word shape; that is, that other available detail about the word, though available to the reader, is not used. However, this question requires further research. The general conclusion we make from the research reported here is that most word identification takes place within a sufficiently narrow region that a great deal of specific letter information is available to the reader. Just what aspects of that information he uses is presently not known.

The second possibility for peripheral information facilitating reading concerned the possibility that readers acquire certain visual information from words far enough into the periphery that they cannot be identified. However, when information from the next fixation is acquired and integrated in the Integrative Visual Buffer (IVB) with the visual pattern from the last fixation(s) the reader can continue his processing of the information in that region by taking additional visual features and adding them to the information he already has. This way, information obtained on one fixation, even though not sufficient to yield word or meaning identification, still contributes to the facilitation of reading.

The data obtained from the Boundary Study lends support to the notion of the IVB. The eye behavior patterns clearly indicated that certain changes in the display from one fixation to another were being noted. Thus the subjects were not operating purely on the basis of visual information available from the present fixation as they read; the relationship of the present visual pattern to the past pattern was noted. However, it should again be pointed out that the region in which a change in the stimulus pattern from one fixation to the next was detected was rather narrow, extending only about 12 or 13 character positions to the right of central vision, and probably much less than that to the left. It appears that this region is about the same as the region within which words can be identified. Thus, it is clear that there is no large region in which some useful visual detail can be acquired (such as word shape, for instance) which is insufficient for word identification, but which can reduce the amount of processing necessary on later fixations. If this occurs, it is confined to a narrow region within which letters can be identified. It is possible, of course, that on a given fixation a word may begin within the region of possible identification, but extend far enough to the right that it cannot be identified. In that case it seems reasonable that the reader may be able to continue his analysis of the visual pattern in that region on his next fixation to permit identification of the word, but at present we are able to provide no evidence that this is so other than that a change in the stimulus pattern from one fixation to the next would indeed be noted in that case.

In summary, then, the studies reported here did not provide evidence in support of either of the suggested means by which peripheral vision may facilitate reading.

The Problem of the Delay in Making the Display Change.

It is appropriate to make some comments about the comparatively long delay in making the display change which was involved in this research. As indicated earlier, we were not aware at the time the studies were conducted of the amount of delay involved. We became aware of this delay later as we further explored the characteristics of the eye monitoring equipment used. This is probably the greatest flaw in the research conducted. It is not possible to say at this point whether replications of some of these studies under conditions with less delay will lead to some different conclusions.

There are two reasons to believe that the delay will be found to have little influence. First, it is well known that there is some degree of visual suppression during the period of the saccadic movement and for some time following it (approximately 50 msec. according to Haber and Hershenson, 1973). The degree of this suppression with complex displays like those involved in reading is not known, since most of the research has used very simple displays. Indications are that the amount of suppression is greater with more complex displays. In any case, the display changes in our research were completed prior to the end of this 50 msec. period of visual suppression. Second, and probably more important, is the phenomenon of masking. The types of display changes used involved replacing one letter with another. Thus it is likely that in most cases the earlier pattern, if it were registered during the initial milliseconds of the fixation, was effectively masked by the new pattern so the earlier pattern was not seen.

Finally, it should be noted that the display changes were not distracting to the subjects, and that they were able to read quite naturally in the experimental situations used. Although in the Boundary Study subjects did occasionally report that they thought they had seen a change take place, it is likely that they did not observe the stimulus change itself, but noted the difference between the pattern on one fixation and that on the next.

It is clear that there is a need for additional research to investigate the effect of delaying the display change in studies such as these, to see how much change can be tolerated before reading behavior begins to show changes.

CHAPTER 11

COMMENTS AND SUGGESTIONS ABOUT EYE BEHAVIOR RESEARCH IN READING

In the study of skilled, silent reading there is little behavior to observe as the reading is taking place. Perhaps that is why there has been a continuing interest over the years in the nature of eye movement behavior during reading. Tinker (1958) summarized much of that research and concluded by indicating that this aspect of reading behavior had been well studied by that time, and that there was probably little further benefit possible from studying eye behavior of readers unless some different approaches were developed for this investigation.

The many studies of eye movement behavior which have been conducted, involving photographic and other techniques for recording data, stand as monuments to the patience of those who engaged in this research. Often the duration of each fixation, its location, and the length of each saccade were carefully measured and recorded, and the mountain of data which results was then summarized in the form of averages for different types of subjects or subjects reading under different conditions or reading different materials. Although the results of these studies were of some interest, showing developmental trends or differences between good and poor readers, they have failed to lead to useful theorizing about the nature of the reading process. More recent studies have begun to become more analytic in attempting to turn to eye movement data to find evidence for or against certain theoretical positions. Some examples of this type of research are the studies by Mehler, Bever and Carey (1967), Wanat (1971), and Abrams and Zuber (1972). This interest has paralleled the growing interest in eye movement behavior in examining scenes, as represented by the work of Yarbus (1967), Loftus (1972), Mackworth and Morandi (1967) and others. A general characteristic of this research is the tendency to turn away from the types of general summary statistics used in the earlier studies, such as average fixation duration and average saccade length, and become much more analytic, looking at more specific aspects of the data and summarizing portions of it in more detailed ways. Often only certain parts of the data are relevant to the experimenters hypotheses, and these are examined in great detail. Although early researchers such as Dearborn (1906) and Woodworth (1938) attempted to do this type of detailed analysis of the data, the lack of adequate linguistic theory probably made it more difficult to identify relevant variables.

There are actually three ways of making use of eye behavior in research on reading (as well as on other visual tasks): (1) data on eye behavior itself may be of primary interest, (2) eye behavior may be used as a basis for collecting data on other types of behavior, and (3) the eye can actually be used as a control device to control certain aspects of the visual stimulus present at a given moment.

Whether eye behavior during reading will be useful in selecting between alternative theories of the reading process depends on the degree to which eye behavior is directed on a moment-to-moment basis by the cognitive processes occurring. Thus the first questions that must be studied are the time required for visual information acquired during a fixation to give rise to different levels of processing, and the degree to which eye behavior reflects moment-to-moment aspects of cognitive processing. The results of the research reported in earlier chapters are heartening, but are just a beginning in these directions. If eye behavior is found to be closely tied to cognitive processing, the door is open for using this type of data to test the adequacy of theories of cognitive processes in reading. However, in reading a single passage a great deal of data is generated, and the researcher must have his theory sufficiently well defined to know exactly what data will be relevant.

Actually eye behavior data can be used from either of two types of reading situations. In one the subject is simply asked to read a passage and the theory is used to make predictions about naturally-occurring eye behavior at specific points in the text. In the other, the text or task situation is specifically set up to lead to the occurrance of disruptions at certain points in the text, or to determine if disruption occurs throughout the text. Manipulating variables in the task or text and observing when disruptions in the eye behavior occurs can be a powerful technique for investigating cognitive processing in reading. This is, of course, the method used in the studies described in this report.

A second use of eye behavior data is as the basis for collecting data on other types of behavior. For instance, the recording of pupil size, EEG patterns, or other behavioral measures during reading, and correlating them with the eye behavior so it can be determined just where the eye was directed when certain patterns are observed in the other data, is likely to be a useful technique for gaining information about the cognitive processes involved in reading. Also, adjunct tasks such as pressing a button when an extra-text signal occurs or when some pattern is observed in the text can be based on eye movements, either triggering a signal off from some aspect of the eye movement pattern or observing when a response occurred with respect to eye position. To use data in this manner it is necessary to have a clear understanding of the size of the perceptual span, so that the experimenter can know what area of the text is actually being perceived and understood when the eye is fixating in a given location.

A third use of eye behavior in research, and one which was developed in the studies reported here, is to use the eye as a control device, controlling certain aspects of the visual stimulus available to the reader at a particular time. This can be a powerful technique for determining what information is acquired from peripheral vision and what from central vision, as well as investigating what aspects of behavior are based on the present stimulus and what on a memorial representation. It can also be useful for exploring the basis for eye movement guidance, since a particular pattern can be set up for a particular fixation during reading, and the effect on eye behavior can be observed. Pilot work we have done suggests that a certain amount of shifting of the text to left and right during a saccade will actually go unnoticed by the reader. If this is so, and if it is possible to anticipate the place the next fixation will occur while the saccade is still in progress; it may be possible to actually move the text on a CRT display to some degree to cause the eye to fixate at the exact location the experimenter desires.

We believe that the ability to use computer techniques to control the nature of the display on a particular fixation, together with the detailed examination of eye behavior data, provides the researcher interested in investigating the nature of perceptual and cognitive processes with the most powerful research tool he has ever had at his disposal. This, we believe, is a new approach to the study of eye behavior which, as Tinker indicated, will be capable of yielding new information about the nature of reading. In particular, it provides the capability for obtaining data on detailed aspects of reading behavior, and thus provides a means of testing the adequacy of present and future theories of reading. We should also mention that this technique provides equally great power for studying questions about other visual tasks, and thus has the capability of becoming a generally important technique in the study of visual perception.

Equipment and Programming Requirements for This Type of Research

Research involving the use of the eye to control the visual pattern place strict requirements on the equipment needed for this research. These requirements are in terms of accuracy of the equipment in identifying eye position, and minimal lag in the eye behavior data as it is being collected.

In terms of accuracy, one faces the question of just how accurate he must be in identifying the direction of gaze for the purposes of his experiment. If the experimenter only needs to know when the subject's eye is returning to begin reading the next line, when he is making a saccadic movement, or whether he is looking at the left or right part of the display, accuracy is of no great concern. However, if he wishes to be able to place a particular visual pattern at a particular location in the periphery during a fixation, accuracy becomes very important. The system used for the research described here had accuracy in the range of $1/2^{o}$ of visual angle on the horizontal dimension. With this, when the equipment indicated that the reader was fixating a particular letter, he could actually be directing his gaze toward a letter up to two character positions away. At times our accuracy was not even that great. Vertical accuracy appeared to be in the range of 2^{o}.

Accuracy of identifying eye position is difficult to achieve. With the type of equipment which simply monitors eye position photoelectrically, or with direct photographing of the eye, there is probably a physiological limit to the degree of accuracy possible which is in the range of 1/4 to 1/2 degree (Cornsweet, 1974). The eye is capable of shifting position in its socket somewhat while still maintaining the same direction of gaze. This shift would be detected by the eye movement equipment as a change in eye position, although the actual direction of gaze had not shifted. The eyeball is surrounded by fatty tissue, and is impelled by strong muscles exerting substantial force to cause it to move quickly. These forces can cause the eye to shift around in the socket, a factor which cannot be eliminated by this type of equipment. Also, keeping the head rigidly fixed is important, a task which is not always easily achieved.

Recent developments of a technique for shining a light into the eye and then tracking two of the resulting Purkinje images promises to provide a technique which tracks the eye with references to itself and the light source, rather than with reference to the head position. This technique is capable of yielding much greater accuracy, reportedly up to 5 minutes of arc (Cornsweet, 1974), but at present is still quite expensive.

A second concern for this type of research is the time taken to produce the display change. Just how much lag can be tolerated again depends on the characteristics of the research. The amount of lag will be a function of time required for three activities: first, the lag in the eyetrack equipment itself;

second, the time necessary for the computer to carry out its functions of detecting the presence of a triggering event and of making the changes necessary to create the instructions for the new display; and third, the time required by the display system to actually realize the new stimulus pattern on the CRT. For instance, if the display change is to occur during a saccade, the total amount of time taken by all three of these activities must be less than about 15 or 20 msec. As indicated earlier, it may be that visual suppression and masking effects may allow this to occur somewhat slower without affecting the data substantially but this needs investigation.

Some suggestions for reducing the time required for these activities will be given in the next section. Here we will discuss briefly the requirements this type of research placed on the eyetracking equipment. It would seem that for this research one should have equipment in which the output signal lags the eye behavior by no more than - or 3 msec. In addition, the amount of noise in the signal is crucial, because this determines how many samples the computer will have to take before it can reliably identify the triggering event, such as the beginning or end of a saccade. Either a longer lag in the signal or greater noise in the signal will increase the amount of time required to produce a display change following some preselected event in the eye behavior pattern.

Some Suggestions for Conducting This Type of Research

The choice of computer and display equipment can be important in determining the speed with which display changes can be effected. Following are some suggestions concerning the choice of equipment. These suggestions will bear on two problems: speeding the computer processing involved, and reducing the time needed to realize a display pattern on the CRT.

There are several characteristics to watch for in the computer system itself. It is assumed that for the study of reading one would want a display system capable of displaying both upper and lower case characters. This being the case, it is important to have a display system which accepts a code of at least seven bits to specify the characters so that it is not necessary to insert shift characters to go from upper to lower case. In our research, the display system used was a Digital Equipment Corporation Model 340. This used a six bit code for specifying characters. In order to change from upper to lower case or back again a special character had to be inserted into the display list. This feature substantially increased the complexity of the programming and reduced the efficiency of the programs.

With a 7-bit code for characters, having a display system that uses standard ASCII code would be most efficient.

Since display change in studying reading involves the manipulation of characters in the display list, efficiency can be gained by having a computer which uses 16-bit words, and which can readily access 8-bit bytes within those words. That way the code for each letter can be readily accessible and changes can be made with the least number of computer instructions.

Even greater efficiency can be obtained by having a computer with a special display processor which operates directly out of the computer's core memory and which can accept jump instructions. With this arrangement, it is possible for the central processing unit (CPU) to construct a display list in its own core memory which is a composite of different segments of the display pattern stored at different locations with jump instructions leading from one to the next. The display can then be changed by simply inserting or deleting jump instructions at the appropriate locations, and there is no need for having to move great numbers of words in core memory in order to place them in the exact order required for the display. If the display processor then operates out of core memory, the CPU can simply give it the address of the beginning of the list and cause it to begin displaying. There is no need to move large numbers of characters from the computer's core memory to the memory of a display device. Having this type of equipment reduces the time required to create the instructions for the display and to make these instructions accessible to the display device. It also reduces the amount of programming required.

Concerning the CRT itself, it is important that it have a short-persistance phosphor so that when a display is changed there is no long-fading image of the previous display remaining on the screen. Also, for the purposes of speed of display change and of controlling just when it occurs a CRT capable of point-plotting or vector generation is to be preferred over raster scan equipment. A CRT which uses a scan method of creating the image has a fixed scan pattern, usually scanning the face of the CRT every 16 msec. to refresh the image. This means that once a display change has been completely set up, there may be a 16 msec. delay before it is realized on the scope. It also means that the amount of the delay depends on where the scan happens to be at the time the change is called for. If the scan happens to be at a point just prior to the part of the image to be changed, the change may be realized in one or two msec. Thus there is an inherent variability ranging from 1 to 16 msec. in how long it takes to cause a change to occur on the screen. It is often possible for the computer to obtain a signal at the beginning of each refresh cycle so it can record how long it was before the display change was made, but it is impossible to actually reduce that variability.

With a point-plot or vector-generation display it is possible to produce patterns on the screen at any time and at any location, limited only by the speed of the display device. Thus, if a certain line is to be changed, it is possible to break the pattern of the refresh sequence and cause the display system to write the new version of that line on the screen when it is first needed. It is also possible, when the pattern being displayed is small (for instance, only two or three lines of text) to drive the refresh rate much higher than 60 per second so that even without breaking the normal refresh cycle the maximum time required before the display change is actually made can be 5 to 8 msec. Thus, with this type of display system it is possible to control the time between calling for a display change and having it appear on the CRT.

Technology in the computer graphics area is advancing rapidly today, and is highly competitive. Computer graphics capability is becoming useful to people in many fields, producing a large market for equipment. This leads to a willingness on the part of companies to invest in improving the necessary equipment. Technology is presently available to support the type of research described here with the sort of equipment suggested. There will undoubtedly be substantial advances made in equipment useful for this research over the next decade, as well as developments which will continue to reduce the cost for the necessary equipment. Within a decade, the computer facilities needed to carry out this type of research may well be readily available in many laboratories throughout the nation.

An Important Distinction in Eye Behavior Research

A frequent criticism of eye behavior research is that the equipment necessary to detect and record the behavior places the subject in a very strange environment which likely produces its own changes on his behavior. This leads us to suggest an important distinction in research involving eye behavior (as well as research of other types). This is the distinction between studying what the person is able to do and what he normally does.

The research which we have carried out is not aimed at identifying what the reader normally does as he reads a book at home or a newspaper on the subway. This research is directed toward finding out what a reader does when he is given a specific task and asked to carry it out to the best of his ability. Thus, we have attempted to make the purpose of the reading task very clear, instructing the subject that he should exert every effort to understand and remember the information in the passages as he reads them. To stress this, we based part of the remuneration for his services on his performance on the test questions. We attempted to use test questions of about the same type throughout an experiment, so that he could readily see exactly what type of information he should be trying to remember from the passage. The reader also was aware that his eye movements were being monitored, and that may lead him to attempt to execute what he believes to be a "good" pattern of eye movements. However, one does not have specific control over eye movements, and particularly as he becomes engrossed in the attempt to gain information from a passage it is difficult to continue the attempt at directing eye movements. It seems likely that given the task at which the reader is asked to do his best, the presence of head holding or eye monitoring equipment has little effect. Thus, we believe that in the attempt to study what subjects are capable of doing in a well-defined task situation, few artifacts are produced by the equipment used in monitoring eye position.

However, if one were to attempt to study what subjects _typically_ do in their reading, he would be faced with quite a different set of problems. Here the task would be to record the subject's behavior in a situation as normal as possible. Most crucial of all would probably be to ensure that the subject is not aware that his behavior is being monitored nor that he would later be tested in any way. Thus, it is not the equipment _per se_ that would affect the subject's behavior, but his perception of the task he is in. Any time a cooperative subject participates in research, he probably attempts to do his best within the task as he perceives it, and this causes him to behave differently than he generally would when unobserved. The task of studying what subjects normally do imposes much stricter requirements on the researcher than does the task of studying what subjects are able to do in a given situation.

Since our research is directed toward an understanding of skilled reading, it seems appropriate to do those things necessary to encourage subjects to exhibit their highest form of skilled reading. Within this context, it is unlikely that the presence of eye monitoring equipment has much, if any, effect on the results of the research.

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