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ABSTRACT

At some time during every fixation a decision is made to move the eyes, directing them to a new location in the stimulus array. To understand the eye movement control processes, three general hypotheses concerning the cognitive basis for deciding to move the eyes were investigated: the saccade (movement) initiation time is determined only on the basis of information obtained prior to the current fixation; the saccade initiation occurs only after all processing of the presently viewed information has been completed; and the saccade initiation occurs when some processing event takes place before the processing of current information is completed. A review of current research indicates that (1) the time of initiating a saccade can be influenced by visual information acquired on the fixation which terminates in that saccade; (2) processing of the information is not necessarily completed by the time of the decision to move the eyes; (3) with fixations too short to process information, the next saccade must be based entirely on prior information; and (4) part of the variability in the saccade onset time may be associated with the amount of processing time elapsing before the information is utilized. (MM)

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WHAT IS THE BASIS FOR MAKING AN EYE MOVEMENT DURING READING?

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Abstract

At some time during the period of a fixation a decision is made to move the eyes. This paper considers possible bases for this saccade initiation decision during reading. Two extreme theoretical positions seem unlikely: that the decision is made without consideration of information from the current fixation or that the eyes are moved when processing of information from that fixation is finished. Alternative explanations which suggest that the eyes are moved after some but not all processing is complete are considered and tested against recent data.

What is the Basis for Making an Eye Movement during Reading?

At some time during every fixation a decision is made to move the eyes, directing them to a new location in the stimulus array. From fixation to fixation, there is a great deal of variability in the time at which a saccade begins. In one set of eye movement records made as people were reading, 92% of the time the eyes were moved between 100 and 500 msec after the beginning of the fixation. The median fixation duration was 230 msec. Variability in fixation duration has been an aspect of behavior that has intrigued psychologists, since it seems likely to reflect differences in processing time required to deal with the information acquired on different fixations. A number of studies have demonstrated relationships between characteristics of the stimuli being fixated and the times, or durations, of these fixations. For reviews of this literature see McConkie (1983), Levy-Schoen and O'Regan (1979), and Rayner (1978).

The purpose of the present paper is to raise an issue which underlies these investigations: namely, on what basis does the mind decide that it is time to move the eyes? Thus, our purpose here is not to account for the variability in fixation times. Instead, the purpose is to understand the eye movement control processes that produce this variability. To do this requires that we investigate the relation between the cognitive processes taking place and the decision to move the eyes. This issue will be discussed within the context of the eye movements of skilled adult readers.

We will consider three general hypotheses concerning the cognitive basis for deciding to move the eyes: (a) the saccade initiation time is determined on the basis only of information obtained prior to the current fixation; (b) the saccade initiation occurs only after all processing permitted by the presently viewed information has been completed; and (c) the saccade initiation occurs when some processing event takes place prior to completing the full processing of the presently viewed information. The first two state positions at opposite extremes and the third takes an intermediate position.

Saccade Initiation Based Only on Prior Information

It has been suggested that during reading there is a considerable lag between the time a part of the text is fixated and the time the information is processed (Shebilske, 1975). Results from studies of the eye-voice span have supported this view, since as one word is being vocalized during oral reading the eyes are usually fixating words further along in the text (Levin, 1979). However, recent eye movement studies have demonstrated that characteristics of a word may influence the length of time it is fixated, thus arguing against a processing lag (Just & Carpenter, 1980). Fixation durations are correlated with several aspects of the words being fixated, including frequency of the word in the language (Kliegl, Olson, & Davidson, 1983), part of speech of the word (Rayner, 1977; Wanat, 1971), predictability of the word in its context (Rayner, McConkie, & Ehrlich, 1978; Zola, 1981), whether or not the word is a reasonable continuation of the sentence as it is being understood (Frazier & Rayner, 1982), and whether or not the word is spelled correctly (Zola, 1981).

The fact that characteristics of words influence the amount of time they are fixated argues against the prior information hypothesis. However, this fact can be explained in either of two ways. First, prior context provides sufficient information about the characteristics of the next word to be fixated that an appropriate fixation time could be allocated on that basis alone. Second, on the prior fixation a peripheral preview of the word to be fixated next could provide sufficient information to determine how long the eyes should remain on that location for the next fixation. Both of these alternatives are ruled out by studies in which a word is changed during the saccade in which the eyes are moving to it. In this case, characteristics unique to the word present on a fixation have been found to influence the duration of that fixation (Rayner, 1975; and two recent unpublished studies from our own laboratory). Characteristics of these words could not have been picked up on previous fixations. Thus, while the time of saccade initiation may be influenced by information from earlier fixations, control is not based exclusively on that information. Currently perceived words have an effect.

Saccade Initiation Occurs When all Processing is Finished

A common assumption about the relationship of cognitive processes and eye movement control suggested in recent literature is that the period during which the eyes are centered on some stimulus unit, such as a word or an object, is the period of time during which it is processed (Just & Carpenter, 1980). Processing is assumed to start at the beginning of this period and to terminate when the eyes are moved. Thus, the triggering event for an eye movement is assumed to be the completion of processing of the presently viewed information. However, this assumption has implications which do not seem reasonable. These are raised by considering the response time of the eyes.

In several studies we have masked the text or made other display changes at a certain time after the onset of selected fixations. When we compare the frequency distributions of the time durations of these fixations with similar frequency distributions for fixations in which no mask occurred, the distributions are identical up to a point 80 to 100 msec following the onset of the mask. At that point, however, there is a sharp dip in the distribution for the mask condition, followed by a large hump in the distribution at a later time. This indicates that for most fixations that would normally have terminated with a saccade more than 80 to 100 msec after the occurrence of the mask, the time of initiation of that saccade was postponed by the experimental manipulation. Fixations that would normally terminate prior to that time were unaffected by the mask. Thus, it appears that the minimum time it takes the eyes to respond to retinal stimulation is about 80 to 100 msec. This is in agreement with results from studies of the saccadic system in which the target to which the eyes are to be moved is shifted prior to the initiation of that movement (Becker & Jurgens, 1979).

The response time of the eyes can be divided into three periods: <u>stimulus transmission time</u>, the time required for transmission of neural activity from the retina to the visual cortex; <u>response transmission time</u>, the time required for transmission of neural activity from the motor cortex to the muscles of the eyes and their latency in beginning to respond; and the processing period intervening between these two. Russo (1978), after reviewing the relevant neurological literature, estimated the stimulus transmission time to be about 60 msec and the response transmission time to be about 30 msec, which is in reasonable agreement with our own estimate of the total response time. Hence, it is assumed that the earliest point at which a stable neural pattern representing the stimulus array is established in the brain is approximately 60 msec following the beginning of each fixation. Prior to that time, the brain is stimulated by the rapidly changing pattern on the retina during the saccade. Likewise, there is a point 30 msec prior to the initiation of a saccade at which the motor signal for that saccade was sent. Brain activity following that point is assumed to occur too late to have any affect on the time of initiation of that saccade.

An implication of this chronology is that if a command is sent to move the eyes only after the processing of the presently available information is complete, then the actual processing time would not be the period of a fixation, but rather would be about 80 to 100 msec less than this (e.g., about 140 msec for a 230 msec fixation.) Furthermore, following the point at which a signal is sent to move the eyes, an average period of 125 msec would pass prior to the stimulation of the brain by input from the next fixation, assuming an average saccade duration of 35 msec. An information processing system which is idle, waiting for new input, almost half the time, is certainly inefficient. It is unlikely that this is an appropriate description of brain activity during reading or other visual tasks where the necessary information is continuously present. Instead, the brain probably initiates a saccade prior to the completion of processing associated with a particular stimulus unit. Evidence in support of this conjecture will be presented shortly.

Saccade Initiation Based on some Intermediate Event

We have argued that neither of the two extreme hypotheses accurately describe the nature of the decision to move the eyes during reading; that is, this decision is not based entirely on information obtained prior to the present fixation, nor does it occur only following completion of all the processing permitted by the presently available visual information. We believe that the remaining alternative is closer to the correct position: the decision to move the eyes is influenced by visual information available during the current fixation, but is made prior to the completion of the processing of that information. The challenge is to identify the basis on which this decision is made. What perceptual or cognitive event indicates that it is time to initiate a saccade? For purposes of present discussion, we will refer to this as the triggering event during the processing sequence (i.e., the processing event which triggers the onset of the next eye movement). We will discuss two examples of possible triggering events: failing to obtain needed visual information and completing word identification.

A Left-to-right Processing Sequence during Fixations

One proposal for the nature of the triggering event is based on the assumption that there is a left-to-right processing sequence during a fixation (McConkie, 1979). It was assumed that during the period of a fixation there is actually a left-to-right progression in the region of text being attended, dealing with successive units of some sort (e.g., letters, orthographic units, syllables or words). This attending of the text is in response to the needs of the language processing activities, providing visual information as required to support those activities. A saccade is then initiated when visual information is needed from a retinal region where acuity is too poor to provide that information. The triggering event in this case would be the failure of the visual system to provide data with sufficient clarity to support the choices required in lower level language decisions, although higher levels of processing may continue beyond that time.

This proposal has the implication that visual information is used from the regions to the left and central parts of the visual field prior to those from the right. Three studies have now sought evidence for this hypothesis, and all have failed (Blanchard, McConkie, Zola, & Wolverton, in press; McConkie, Underwood, Zola, & Wolverton, Note 1; and Slowiaczek & Rayner, cited in Rayner, 1983). Thus, at present there is no evidence for such a progression of attention during fixations in reading.

Saccade Initiation at the Completion of Word Identification

Another reasonable hypothesis is that there is some point during a fixation at which the processing of visually provided information is completed. At that point, the visual system is ready to deal with new input and the eyes are advanced, positioning them to deal with the next visual region. In the meantime, higher processing continues using the visually provided information to advance the understanding of the text. If this were the case, a reasonable candidate for the triggering event would be the completion of word identification. Evidence for this possibility comes from studies, mentioned earlier, which indicate that characteristics of words which are known to influence their ease of identification, such as their cultural frequency, also affect the time they are fixated during reading.

While this is an appealing possibility, recent results from work in our laboratory are not in harmony with it. In one study, as subjects were reading, there were certain fixations on which all letters to the left of the directly fixated letter, or all letters more than three to the right of it, had been replaced by other letters. Normal text returned during the following saccade. Thus, the study investigated the effect of having erroneous letters present at specific retinal regions on individual fixations during reading. We assumed that the presence of erroneous letters would disrupt the word identification process and that the difficulties produced would increase processing time. This, in turn, should delay the saccade onset if it is normally dependent on successful word identification, resulting in longer fixations when the errors are present (McConkie, Underwood, Wolverton, & Zola, Note 2).

When the erroneous letters lay to the left of the fixated letter, the duration of that fixation was increased, as expected. However, further examination indicated that the increased fixation time occurred only in the 21% of the cases in which subjects made a regression on the following saccade. In the cases where the following saccade was a forward movement, there was no change in the fixation duration, as compared to fixations on which there were no errors. The following fixation was longer than normal, and the frequency of regressions on the following saccade was greatly increased, indicating that the erroneous letters had been perceived.

Even more striking were the results when the erroneous letters were in the right part of the visual field. Here we found no effect on the duration of the fixation on which the errors were present, although the following saccade was shortened. Again, effects on later fixations and saccades indicated that the subjects had perceived the errors.

In this study subjects encountered errors on certain fixations in the words they were reading, and these errors clearly disrupted their processing. Yet in most cases the duration of the fixation on which the errors occurred was not affected. These results do not support the hypothesis that the eyes are moved only after word identification occurs. If this were the case, we would expect to see a change in the frequency distribution of the durations of the fixations on which errors were present. The errors should create processing difficulties which would delay the following saccade. Such effects were found only under limited circumstances. In the great majority of cases only later fixations were affected.

What we seem to be dealing with, then, is a system in which the characteristics of the words being identified influence, at least sometimes, the time of initiating the following saccade when processing proceeds smoothly. However, when processing is disrupted by errors lying three or more letter positions to the right of the fixated letter, or in many cases by errors to the left of the fixated letter, then the decision to move the eyes is not postponed in order to provide additional time dealing with the problems arising. Rather, the eyes are advanced at the time they would have been without the errors. Then additional processing time is gained either by lengthening the following fixation or by later returning the eyes to the region where the problems had occurred.

There is another finding which relates to the hypothesis being considered here. Not only do the characteristics of the fixated word influence the duration of the fixation on it, as described earlier, but if the following saccade sends the eyes beyond the next word, then that next word also affects the fixation (Hogaboam, 1983; Kliegl, Olson, & Davidson, 1983). Thus, there is evidence that in cases where a saccade skips over a word, that word was identified during the prior fixation. This being the case, we might expect the system to require more processing time in the case where the following word was skipped than in the case where the eyes were sent to it, since an additional word was apparently read in the former case. This suggests that there should be a correlation between the duration of a fixation and the length of the following saccade. Neither of these predictions is correct, however. Skipping a word does not increase the prior fixation duration (Hogaboam, 1983) and the correlations between fixation duration and the length of the following saccade is near zero (Andriessen & deVoogd, 1973; Rayner & McConkie, 1976). Thus, another reasonable prediction from the word identification hypothesis is not correct.

As yet, we have no direct support for the hypothesis that the completion of word identification is the triggering event for a saccade. It will be necessary to conduct studies designed more specifically to test this hypothesis, but at the present time it does not look promising.

Further Considerations

The data from another recent study were analyzed to determine how long a fixation had to be in order to be influenced by erroneous letters lying to the left of the fixated letter (McConkie, Underwood, Zola, & Wolverton, Note 1). As in the study described earlier, on certain fixations all letters to the left of the directly fixated letter were replaced by erroneous letters. The frequency distribution of durations of these fixations was compared to that of fixations on which there were no errors. It was found that the distributions were identical in the lower fixation duration range but separated in the 140-160 msec range. Thus, it appears that a fixation must be at least 140 to 160 msec long in order to be long enough to be influenced by the orthographic characteristics of the text.

One implication of this result is that fixations which are shorter than 140 msec are too short for even the orthographic aspects of the text to have an influence on when the saccade occurs. In one set of data of college students reading a 417 word passage describing the early history of Alaska, 10% of the fixations were less than 140 msec and some were even shorter than the response time of the eyes. In these cases the saccade initiation times must be determined without input from the present fixation. Thus, for some fixations, the triggering event has nothing to do with the processing of information obtained on that fixation. However, this occurs on relatively few instances.

In another study, as subjects read the text was masked with a line of X's either 50, 80 or 120 msec after the onset of each fixation (Blanchard, McConkie, Zola, & Wolverton, in press). The mask lasted for 30 msec, and then the text returned. There were certain word locations in the text that could be occupied by either of two words which differed by only a single letter. On fixations in the region of these words, the distinguishing letter was changed following the mask, and then changed back during the following saccade. Thus, during the first part of each fixation one word was in that word location, and during the latter part of the fixation the other word was present. We wanted to find out whether subjects would perceive this change, and, if they did not, whether they would report having seen the word present at the beginning or end of the fixation.

The results indicated that subjects reported having seen only one of the two words 65% of the time, and that in these cases, the fixation durations were the same as those from control instances in which the text was masked but the word was not changed, thus giving no evidence that the word change was disruptive. Furthermore, in these cases subjects sometimes reported having seen the word present at the beginning of the fixation, and sometimes the word present at the end. One interpretation of the results is that the time during the fixation at which the visual information from a word is utilized in the reading process varies from fixation to fixation. This is referred to as the <u>Variable Utilization Time Hypothesis</u>. It suggests that in reading there is a specific time during the fixation at which the information provided by a word is brought into play in the language processing, and that this time can occur at any time during the fixation when the information is needed. If this hypothesis is accurate, then much or even most of the variability in fixation times is variability in the amount of time that elapses prior to the utilization of the fixated word, rather than variability in the processing time of the word itself. This contrasts with the notion that processing during reading proceeds in stages time-locked to the beginning of each successive fixation, as with Just and Carpenter's (1980) initial stage, entitled Get Next Input (McConkie, 1983). While this does not clarify exactly what serves as the triggering event for a saccade, it may contribute to an understanding of why the time of that event is so variable.

Conclusions

At some point during a fixation a message is sent to the ocular muscles to initiate an eye movement which will cause the eyes to move to some new location in the display. The purpose of the present paper is to consider the nature of the processing event which triggers this message. Present research suggests the following statements.

1. The time of initiating a saccade can be influenced by visual information acquired on the fixation which terminates in that saccade. Cultural frequency and orthographic characteristics are two aspects of the text stimulus which can have this influence.

2. However, processing of the information acquired during a fixation is not necessarily completed by the time of the decision to move the eyes. If it were, the system would spend much of its time in waiting for the next visual input.

3. At least some characteristics of the stimulus can only influence the saccade initiation time if a saccade has not occurred by a certain time.

For instance, the presence of orthographically irregular letter strings on a fixation only affect the durations of fixations lasting at least 140 msec; shorter fixations show no effect.

4. As a corollary to the point just made, some fixations appear to be too short to be affected by any visual information acquired during those fixations. In these instances, then, the initiation of the next saccade must be based entirely on information available prior to the fixation.

5. With the exception of the shortest fixations, the saccade initiation time is probably determined to some degree by information acquired on that fixation, but not by the completion of the processing of that information. What, then, is the intermediate processing event which is linked to moving the eyes? Present data do not support either of the two possibilities considered here: namely, that a left-to-right consideration of the text is completed, or that word identification is completed.

6. Part of the variability in the saccade onset time may be associated with the amount of processing which takes place before the information available from the present fixation is utilized.

These suggestions fall far short of specifying the cognitive events accompanying the initiation of a saccade. However, they do question several reasonable alternatives and place constraints on future theorizing.

Finally, it may seem reasonable to postulate simply that the eyes are moved when there is a shift of attention to a new region of text. While this may well be true, it still leaves open the original question, which would now be stated as: What is the cognitive event which indicates that it is time to shift attention to a new region, and hence initiate an eye movement?

It is our hope that the above discussion will stimulate research and theorizing on the nature of the triggering event for saccades in on-going tasks like reading. Further knowledge on this issue will increase our understanding of what fixation time data can tell us about processing time in these tasks.

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