Technical Report No. 305

INSTRUMENTATION CONSIDERATIONS IN RESEARCH INVOLVING EYE-MOVEMENT CONTINGENT STIMULUS CONTROL

George W. McConkie, Gary S. Wolverton
and David Zola

University of Illinois at Urbana-Champaign

January 1984

Center for the Study of Reading

READING EDUCATION REPORTS

UNIVERSITY OF ILLINOIS AT URBANA-CHAMPAIGN
51 Gerty Drive
Champaign, Illinois 61820

BOLT BERANEK AND NEWMAN INC.
50 Moulton Street
Cambridge, Massachusetts 02238

The National
Institute of
Education
U.S. Department of
Education
Washington, D.C. 20208

CENTER FOR THE STUDY OF READING

Technical Report No. 305

INSTRUMENTATION CONSIDERATIONS IN RESEARCH INVOLVING EYE-MOVEMENT CONTINGENT STIMULUS CONTROL

George W. McConkie, Gary S. Wolverton and David Zola

University of Illinois at Urbana-Champaign

January 1984

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

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

This work was supported by Grant MH 32884 from the National Institute of Mental Health to George McConkie and the National Institute of Education Contract No. HEW-NIE-C-400-76-0116 to the Center for the Study of Reading. To appear in A. G. Gale & C. W. Johnson (Eds.), The Proceedings of the Second European Conference on Eye Movements, Amsterdam: North Holland Publishing Co., in press.

Abstract

In the study of perception during reading the use of eye movement contingent control of the stimulus display has proved to be a useful research technique. With such a system it is possible to experimentally manipulate, in real time, the characteristics of the stimulus display that is present on selected fixations as reading is in progress, and to observe the effects of the manipulation on the eye movement pattern. This technique can also be used in the study of other on-going, visually based tasks. This paper provides examples of how the technique has been used, and describes a number of the instrumentation concerns which are important to consider when setting up a system to do this type of research.

Instrumentation Considerations in Research Involving Eye-movement Contingent Stimulus Control

There are three possible reasons for monitoring eye movements in psychological research. First, the eye movement records can serve as a source of data. Sometimes aspects of these data, such as the durations of fixations or the lengths or directions or velocity patterns of the eye movements, are the dependent variables in the study. At other times, the data are used to determine which trials should be excluded from analysis. Second, real time information about the eye movements can be used as a basis for making on-line experimental manipulations in the stimulus. For example, a tone can sound or a change can be made in the visual array when the eyes fixate a certain location. Third, real time information about the eye movements can be used as a basis for other forms of measurement. EMG recording can be enabled only when the eyes fixate a certain location, or EEG data can be selected and averaged based on the location and/or movements of the eyes.

The focus of the present paper will be on the second of these alternatives: using eye movement monitoring as a basis for making stimulus manipulations. For a number of years we have been studying the nature of the perceptual and eye movement control processes taking place as people read. This required the development of a computer-based system that was capable of monitoring people's eye movements as they read, and, on the basis of that information, making real time changes in the text from which they were reading (McConkie, Zola, Wolverton, & Burns, 1978).

Using this system, we are able to allow subjects to read text displayed on a cathode-ray tube (CRT), and as they are reading, to manipulate the stimulus pattern that is present in the region where they look for a particular fixation, or at a particular time during the fixation. We then examine the effect which these display manipulations produce on the eye movement patterns as a way of learning about the processes being studied.

These techniques have been extremely fruitful in investigating aspects of the perceptual processes as they occur during reading (McConkie, 1983; Rayner, 1983). They have also been used to study perception in simpler tasks (Bridgeman, Hendry, & Stark, 1975; Irwin, Yantis, & Jonides, 1983; Levy-Schoen & Rigaut-Renard, 1981). We believe that they could be equally useful in the study of perception in other visually-based tasks, such as visual search and picture perception. Anticipating that other researchers are likely to attempt to develop research of this sort, the purpose of the present paper is to describe some of the considerations that must be taken into account in selecting equipment for this type of research. While it will deal primarily with eye movement contingent control of visual displays, many of the points made will also be relevant to on-line control of other forms of stimulus manipulation or data collection.

In order to illustrate some of the perceptual issues which can be investigated using these techniques, we will briefly describe four examples from our own research.

1. We were interested in whether or not it is necessary for the eyes to be centered at the exact location to which they are sent on a saccade in order for processing to proceed normally. This was investigated by causing certain fixations to be "misplaced" slightly as people were reading. During certain saccades, the text was shifted two character positions left or right on the CRT, so that when the eyes stopped for the next fixation they were centered at a location different from where they normally would have been (McConkie, Zola, & Wolverton, Note 1; see also O'Regan, 1981).

2. In order to determine whether visual information is acquired and used from specific visual regions during fixations in reading, the letters in these regions were replaced with other letters on certain fixations. Thus, use of this information would produce processing difficulties, discernible in the eye movement pattern (Underwood & McConkie, Note 2).

3. We investigated whether particular aspects of the visual stimulus pattern present on successive fixations are brought together into a single mental representation. Certain characteristics of the text pattern were changed during occasional saccades, such as the spacing between words or the forms of the letters. If the system attempts to integrate these aspects of the visual array across successive fixations some degree of difficulty should be encountered, again being reflected in the eye movement pattern (McConkie & Zola, 1979; Rayner, McConkie, & Zola, 1980).

4. We studied the time characteristics of the perception and eye movement systems by producing changes in the display at specific times following the onset of a fixation and observing the effect which this had on the shapes of the distributions of fixation times (Wolverton, Note 3; McConkie, Underwood, Zola, & Wolverton, Note 4).

These types or studies make strong demands both on the eye movement monitoring equipment and on the equipment used to produce and manipulate the stimulus. Decisions in the choice of equipment to purchase or develop are crucial; wrong choices can greatly limit the research which can be done and introduce undetected artifacts into the data. Computer programming must be tight and well controlled. However, the nature of the constraints on the equipment and programming depends on the characteristics of the research to be carried out: these constraints are very strong for some types of studies and less strong for others. In order to describe the concerns that must be taken into consideration we will discuss two cases in which eye movement contingent control of a CRT display is required, one in which the display must be changed during the period of a saccadic eye movement, and a second in which it is necessary to make a change at some time after the beginning of a fixation.

Changing the Display during a Saccade

In order to change the stimulus display during a saccade, there are four things that must be accomplished prior to the beginning of the following fixation: 1) detecting the onset of the saccade, 2) determining that this is the saccade on which a change is desired, 3) changing the computer's display instructions so they can create the new image, and 4) actually having the new image present on the CRT. How much time there is to complete all this depends on the length of the saccade on which the change is desired. In reading, the shortest saccades can be completed in less than 20 msec, for instance. If the task is to look from one specified point to another which is some distance away, this time can be 90 msec or more, depending on the distance of the two points.

Detecting the Onset of the Saccade

How early in the saccade the eye movement monitoring system can detect that the eyes have begun to move depends on several factors. First is the speed of throughput of the eye movement monitor. Given that the monitor indicates that the eyes are at a given position, how much time has passed since they were actually in that position? With the scleral reflection approach to eye movement monitoring this throughput time can be a matter of no more than three or four msec or even less, unless longer delays have been introduced into the circuitry in order to filter out noise. With some forms of filtering, this delay can be over 20 msec. Therefore, in some cases a saccade could be completed before the eye movement monitor indicates that it has begun. With equipment using television technology to photograph the eye, and then processing the digitized image to identify the eye position, the eyes can begin to move during the 16 msec period required to complete one scan of the eye. Whether the output shows the eyes beginning to move depends on when during the scan the movement began, and whether the critical information in the image used to track the eyes lies toward the top or bottom of the frame. Thus, it would be quite possible to miss the beginning of the movement in one frame, and only detect it in the next, so that a short movement may be finished before its initiation is detected.

The second factor influencing how early an eye movement can be detected is the rate at which the eye position is sampled. How much time elapses between taking successive samples of the eyes' location? At least that much time can pass after the eyes begin to move before that movement is detected. In our own work we sample the eye position every msec, and computer how much movement has occurred in the last 4 msec. If this movement is above threshold, we then require a certain number of additional samples to be above threshold, as well. Depending on other factors, it may be possible in this way to reliably detect the onset of a saccade within a relatively few msec of the time that the eye movement signal begins to show the movement.

The third factor is the amount of noise in the eye movement signal. The noise level essentially defines a region of indeterminacy around the eye's position. The eye movement signal must move outside this region before an eye movement can be reliably detected. If the noise level is high, then the eyes must move further before the movement can be reliably detected. This increases the likelihood that an eye movement sample will fail to indicate that the eye has begun to move, thus delaying the time until the movement is detected.

These three factors are additive. That is, the total amount of delay which can occur in detecting the onset of a saccade is at least the total of the maximum delay possible from each of these three sources. This total delay can be sizeable. A combination of slow throughput, slow sampling rate, and high noise level can result in total delays of 50 msec or more. In this case, all but long saccades would be completed before their initiation was detected. The combination of fast throughput, high sampling rate and low noise level can permit saccades to be reliably detected within less than 10 msec after their initiation.

Determining Whether a Change Should Occur on this Saccade

The amount of time required for this stage varies widely, depending on the requirements of the study. For example, in the simple case, display changes are called for on every saccade, every leftward saccade, or on the 5th, 10th and 15th saccades made. In a more complex case, a change is made only if the prior fixation is in a certain region of the display.

The most difficult cases are those where the display change is made contingent on aspects of characteristics of the saccade itself. For instance, a change may be desired only if the saccade will be of at least a certain length, or will take the eyes to a certain location. These decisions require waiting during the saccade to see if it reaches a certain velocity or passes a certain boundary, or until sufficient information is available to permit an accurate prediction of the location of the following fixation. Obviously, these latter types of decisions require eye movement data obtained at high sampling rates and with low noise, and they leave only the latter part of the saccade time available for making stimulus changes prior to the beginning of the following fixation.

Making Changes in the Display Instructions

The time required to make changes in the display instructions can also be quite variable from study to study. This time consists of the total time required to calculate the necessary changes, and, if necessary, to transmit those changes (or a copy of the changed list of display commands) to the display device. In the simplest case, alternative images have been previously prepared and are present within the computer's high-speed memory. The CPU, or a special display processor having access to high-speed memory, controls the display device directly. In this case, when a change in the display is required, it is simply a matter of taking display commands from a different region of memory. Many display changes can be accomplished in this simple manner. On the other hand, if there are many possible forms which the next display can take, contingent upon eye position, then each alternative must be computed when it is needed. This computation time varies with the complexity of the displays involved. Also, once the display commands have been modified, if they must be transmitted to the memory of the display device, there will be an additional delay, the amount of which depends on the speed of transmission of information between the devices involved.

Realizing the Image on the Display Device.

The most common electronic displays for psychological research involve illuminating the image on the screen a point at a time. This is done either as a complete raster scan or in a sequence more optimally related to the characteristics of the display itself, using a point-plotting device. In either case, the process takes time. The amount of time for raster displays is usually either 16 or 32 msec; for point-plotting equipment the time depends on the complexity of the image and the efficiency with which it was coded. However, this does not mean that the image can be realized on the screen within these period of time after they are called for. In many instances, it is not possible to begin "painting" a new image on the screen until the beginning of a refresh cycle. That means that with a 16 msec refresh cycle, if a new image were called for just after the beginning of a cycle, it would be necessary to complete that cycle and then to display the new image on the next cycle. Thus, a total of 31 msec could elapse before the initial display of the next image were complete. With a 32 msec refresh rate, that time could be as much as 63 msec. Thus, substantial delays can result at this point.

Two approaches can be taken to reducing this source of delay. The first is to use simple images with a point-plotting device so that the image can be refreshed rapidly. The second approach is to have the facility to begin displaying a new image in mid-cycle. With a point-plotting device it is possible to break the cycle at any point and begin displaying an alternative image. Thus the change can be completed within the refresh cycle time. Also, with some graphics equipment it is possible to point the controller to a new region of high-speed memory at the end of any horizontal scan during the refresh process. It is therefore possible to display the new image within the period of a single refresh cycle after it is requested.

Finally, some recent raster scan graphics controllers have a degree of flexibility in the refresh rate, which makes it possible to attain refresh cycles requiring less than the normal 16 msec period. Further development of this equipment could greatly facilitate eye movement contingent display control where complex displays are required.

Summary

When making a change in the visual display during the period of a saccadic eye movement, there are a number of steps which must occur within a time ranging from 20 to 90 msec, depending on the length of the saccades involved in the study. During this period of time it is necessary to detect the onset of the saccade, determine whether a display change should occur during this saccade, make the necessary modifications in the display instructions within the computer and perhaps transmit these to the display device, and actually realize the new image on the screen. In order to accomplish this, it is necessary to have equipment with the required characteristics and to program it with a concern for minimizing delays.

Desirable system characteristics are the following:

1. Eye movement monitoring equipment with fast throughput, low noise, and which yields new information with high frequency.

2. A program which samples the eye position with a high frequency, which can detect saccade onset and make the decision about whether to initiate a display change as early as the study permits, and which minimizes the amount of computation involved in changing the image.

3. A display device capable of being rapidly refreshed and of initiating the presentation of a new image part way through the refresh cycle.

How many non-optimal characteristics can be tolerated in the equipment depends, of course, on the demands of a given study.

Changing the Display during a Fixation

When it is necessary to make an experimental manipulation at a certain time after the beginning of a fixation, many of the concerns described in the prior section again apply. This is particularly true if the change must occur relatively early in the fixation, such as 20 to 50 msec after it begins. Again, one is faced with the problems of carrying out all of the steps which are required in the time which is available. If the change is not required until 100 msec or more after the onset of the fixation, more time is available for the steps required.

However, there is another concern which arises when dealing with changes during a fixation. When manipulating the stimulus during saccades, there is less concern about just when the change takes place. It has been our experience that the visual system is quite insensitive to display changes made while the eyes are moving. Blanking out the display is detected, but replacing text strings with other strings is not. Thus, it is not critical exactly when during the saccade the change is made. However, when making changes during the fixation, the timing of the change often becomes the point of the research. In order to make the change at the specific time desired, it is necessary to accurately identify the beginning of the fixation, since that is the base for timing. There are two problems which arise here, one having to do with the equipment being used, and the other with characteristics of the eye movements themselves.

With respect to the equipment used for monitoring the eye movements, all of the concerns described earlier related to detecting of the onset of a saccade apply here in detecting the onset of the fixation. The same sources of delays are present. Furthermore, there can be considerable variability in how soon after the beginning of a fixation it is detected. For instance, with a 16 msec sampling rate there is an inherent 16 msec variability in when the fixation is said to begin. With the noise in a relatively clean signal this variability can become 32 msec. With a noisy signal, the variability increases still further. Variability in determining the point from which timing should begin results in variability in the time that elapses from the actual beginning of the

fixation until the display change takes place. Furthermore, as described earlier, characteristics of the refresh process can add variability to the amount of time that elapses from the time a display change is called for until it is actually displayed. How much variance in timing can be tolerated depends, of course, on the nature of the experiment. If relatively precise control is needed, equipment for the research must be selected with care.

The preceding discussion was based on the assumption that an accurate, noise-free signal sampled at a high rate would clearly indicate when a fixation begins. However, this is not the case. As the eyes decelerate during a saccade there is typically a period of overshoot, with the signal coming to a peak and then moving back the other direction and gradually stabilizing. This probably represents a settling time of the eyes, during which they center themselves in the socket, and perhaps regain their shape after responding to the forces of the ocular muscles. This overshoot is exaggerated in equipment which monitors reflections from the lens as well as from the eye's surface, suggesting that the torque applied to the eye may induce distortions in the internal parts of the eyes, which must also return to normal at the end of the eye movement. The problem, of course, is what to identify as the beginning of the fixation; whether this should be the peak of the overshoot at which time the forward component of the movement is completed, whether it should be at the end of the settling period, or whether it should be at some other time. There is no clear answer at the present time and this adds variance both within and across studies in this area. It is our contention that the beginning of the fixation should be identified with the point at which visual information of the type needed for the task being used can first be acquired from the display. We will shortly be conducting research to attempt to identify where this point occurs.

One final comment should be made with regard to the amount of variability involved in identifying the beginnings of saccades and fixations. In many eye movement studies the primary data of interest are the durations of fixations. The duration of a fixation is, of course, simply the time from the end of one saccade until the beginning of the next. The error variance in fixation durations, then, is a sum of the error variance in identifying each of these defining events, since it is reasonable to assume that the two sources of variance are uncorrelated. Thus, while the previous discussion has been concerned primarily with the problems which this sort of variance produces for employing eye movement contingent stimulus control, in fact many of the same concerns arise even in the case in which no display changes are required, but where accurate eye movement data are desired. Those factors that contribute to accurate identification of saccade and fixation beginnings also contribute to accuracy in fixation duration data.

Summary

Making display changes at precise times following the onset of a fixation requires the ability to reliably detect when the fixation begins. This requires equipment which has fast throughput, a low noise level, and which can be sampled at a high rate. Even then, noise free eye movement data would not indicate a clear point at which the fixation begins. This adds another source of variance. Research aimed at identifying at what point in the fixation perception of visual detail is possible may help resolve this problem. Finally, the eye movement monitoring issues which have been discussed are not only of importance in controlling the stimuli contingent upon eye movements. They are also of concern if the desire is to obtain an accurate measure of fixation times.

Additional Concerns

There are two additional equipment concerns that should be mentioned. First, the necessity of making fast display changes requires that the display image fade quickly. Thus, for CRT displays a fast-decay phosphor is required. Second, rapid sampling of the eye position generates a great deal of data, requiring large amounts of storage space. It may seem reasonable to bypass this requirement by doing on-line reduction of the data as they are being collected. We believe this to be unwise. Having a complete data record is useful for three purposes. If the time at which display changes take place is recorded in the data, for instance by setting a bit pattern in a data word collected at the time a display change is called for, it is possible to verify that the system was operating properly. In this type of research, there is no other way to be sure that this is the case. Also, more accurate data reduction programs can be developed when reduction is off-line. There are not the time limitations, and the program can move forward or backward along the data stream to find saccade beginnings and endings. Finally, there are frequently irregularities in the eye movement data, probably resulting from blinking and squinting. These can lead to strange patterns in the reduced data, and examining the raw data can indicate whether or not these data are usable.

An Example

In our eye movement contingent display control system, we use the SRI Dual-Purkinje Image Eyetracker (Cornsweet & Crane, 1973). It is claimed to have a throughput of about 4 msec. The noise level places a band of indeterminacy around the mean signal value equivalent to less than 2 min of arc of eye movement. Thus, an eye movement can be reliably detected by the time the eyes have moved 5 min of arc or less. We sample the eye position every msec, checking the distance moved over the preceding 4 msec. The peak of the overshoot at the end of the saccade is detected by a change in direction of the values being obtained over a 4 msec period, and the end of the overshoot period is detected by finding less than 4 min of arc of movement over a 4 msec period. Furthermore, we have found that we can predict the location of the next fixation, usually within 40 min of arc, once we have identified the point of peak velocity within a saccade.

The eye movement signal is sampled by a PDP-11/40 computer, which, in addition to the CPU, has a display processor which has access to high-speed memory. The display processor controls a point-plotting CRT. With this, we can present a single line of text with a 3-msec refresh rate. Thus, the entire line can be changed within 3 msec.

Most of our studies involve a relatively few alternate lines which can be displayed, contingent upon the eye's location and state. Thus, the alternative lines are typically stored in high-speed memory. Display changes simply involve the CPU directing the display processor to a new region of high-speed memory where an alternative display list resides. Thus, the change requires minimal time, with no transmission time required.

In our most recent study, we were able to detect the onset of a saccade, predict the location of the following fixation, and change the line of text if the fixation was going to be on a particular word, within the period of all but the shortest saccades. In this way, it was possible to study the value of obtaining peripheral visual information from a word on its later identification.

The ability to exert eye movement contingent control over visual and other stimuli provides a powerful research technique which permits detailed investigation of perception and eye movement control as people are engaged in on-going tasks. This technique has been used in the study of reading and in some simpler tasks. It should now be extended to the investigation of visual search, picture perception, and other visually-based tasks.

Reference Notes

1. McConkie, G. W., Zola, D., & Wolverton, G. S. How precise is eye guidance? Paper presented at the annual meeting of the American Educational Research Association, Boston, April, 1980.

2. Underwood, N. R., & McConkie, G. W. Perceptual span for letter distinctions during reading (Tech. Rep. No. 272). Urbana: University of Illinois, Center for the Study of Reading, 1983.

3. Wolverton, G. S. The acquisition of visual information during fixations and saccades in reading. Paper presented at the annual meeting of the American Educational Research Association, San Francisco, Calif., 1979.

4. McConkie, G. W., Underwood, N. R., Zola, D., & Wolverton, G. S. Some temporal characteristics of processing during in reading. Unpublished manuscript, University of Illinois, 1983.

References

Bridgeman, B., Hendry, D., & Stark, L. Failure to detect displacement of the visual world during saccadic eye movements. Vision Research, 1975, 15, 719-722.

Cornsweet, T. N., & Crane, H. D. Accurate two-dimensional eye tracker using first and fourth Purkinje images. Journal of the Optical Society of America, 1973, 63, 6-13.

Irwin, D. E., Yantis, S., & Jonides, J. Evidence against visual integration across saccadic eye movements. Perception & Psychophysics, 1983, 34, 49-57.

Levy-Schoen, A., & Rigaut-Renard, C. Pre-perception ou activation motrice au cours du T. R. oculomoteur? In J. Requin (Ed.), Anticipation et comportement. Paris: Centre National de la Recherche Scientifique, 1981.

McConkie, G. W. Eye movements and perception during reading. In K. Rayner (Ed.), Eye movements in reading: Perceptual and language processes. New York: Academic Press, 1983.

McConkie, G. W., & Zola, D. Is visual information integrated across successive fixations in reading? Perception and Psychophysics, 1979, 25, 221-224.

McConkie, G. W., Zola, D., Wolverton, G. S., & Burns, D. D. Eye movement contingent display control in studying reading. Behavior Research Methods and Instrumentation, 1978, 10, 154-166.

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

Rayner, K. The perceptual span and eye movement control during reading. In K. Rayner (Ed.), Eye movements in reading: Perceptual and language processes. New York: Academic Press, 1983.

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

This page is intentionally blank.