Behavior Research Methods & Instrumentation
1979, Vol. 11 (2), 164-171

SESSION V
SYMPOSIUM ON EYE MOVEMENT RESEARCH

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Eye movements and cognitive psychology: On-line computer approaches to studying visual information processing

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Advantages of using on-line computers to record eye movement data are discussed. These advantages include computer scoring of eye movement data, greater accuracy in identifying the location of a fixation, greater accuracy in determining timing variables such as saccade duration and fixation duration, and the capability of controlling stimulus presentation as a function of eye location. Emphasis is placed on the latter of these advantages. The characteristics of an on-line eye movement recording system are briefly described, followed by a description of the research using such a system to investigate reading, integration of information across eye movements, eccentric vision, and picture processing and visual search.

During the past few years there has been a tremendous increase in the number of experimental reports that have utilized eye movement data to investigate various types of cognitive processes. A recent review (Rayner, 1978a) indicates that eye movement data are being widely used to investigate reading, picture viewing, visual search, language processing, mental rotation, imagery, and other types of cognitive activities. One of the major reasons for this burgeoning interest in eye movement research is the technological advances over the past few years that have made it possible to collect eye movement data on-line. In the present paper, advantages of using on-line computers to record eye movement data are discussed. In addition, the characteristics of an on-line eye movement recording system and cognitive research using such a system are discussed.

ADVANTAGES OF ON-LINE COMPUTERS FOR RECORDING EYE MOVEMENTS

There are a number of advantages of recording eye movement data on-line over methods that use photographic techniques or strip-chart recorders. These advantages include (1) computer scoring of data, (2) greater accuracy in identifying the location of a fixation, (3) greater accuracy in determining timing variables such as saccade duration and fixation duration, and (4) the capability of controlling stimulus presentation as a function of eye location. Of these advantages, the latter has probably had the most significant impact on recent research on cognitive processing.

Preparation of this paper was supported in part by Grant BNS76-05017 from the National Science Foundation and by Grant HD 12727-01 from the National Institute of Child Health and Human Development. The author would like to thank Arnold Well and Alexander Pollatsek for their comments on an earlier draft. Requests for reprints should be addressed to Keith Rayner, Department of Psychology, University of Massachusetts, Amherst, Massachusetts 01003.

Prior to 1973, research utilizing eye movements to investigate cognitive activities generally required investigators to (1) photograph eye movements with the stimulus superimposed on the film and then play the film back one frame at a time for manual scoring, or (2) manually score data (printed on an X-Y plotter) that had been collected using electrooculographic or corneal reflection techniques. Some rather monumental studies utilizing these techniques characterize the history of eye movement recording in experimental psychology. It is noteworthy that most of the basic facts we know about eye movements were obtained using these rather crude techniques. It is a tribute to early eye movement researchers that most of their observations hold up when their experiments are replicated using more sophisticated equipment. However, the early techniques were plagued by questions concerning accuracy of scoring, and data analysis was an extremely time-consuming activity.

Computer Scoring of Eye Movement Data

At the simplest level, one obvious advantage of computer technology is that eye movement data can be

  0005-7878/79/020164-08$01.05/0

scored by the computer rather than by hand. A simple reading experiment involving subjects reading short passages of text as their eye movements are recorded may easily require hundreds of hours to analyze the data by hand. Computers can dramatically reduce the time and cost of data analysis and rapidly provide printouts with the reader's fixations marked in terms of duration and sequence. Kundel and Nodine (1973) have described a system by which photographic records can be scored by computer. But a far more efficient technique is to record the data on-line and simply program the computer to print out (1) the subject's raw data, (2) the passage the subject read, marking the location, duration, and sequence of fixations, and (3) summary data such as means and medians. Such a technique is now being used with video recording systems (Just & Carpenter, 1976) and with infrared corneal reflection systems (McConkie, Zola, Wolverton, & Burns, 1978; Reder, 1973).

In addition to reducing the time and cost involved in analyzing data, computer scoring also enables the experimenter to reanalyze different aspects of the data at various points in time after the data have been collected. For example, if an experimenter is interested in reading and the data have been collected on-line and stored on a disk, it is possible to go back later and examine various aspects of the data that were not of central interest when the experiment was initially carried out. Suppose an experiment was initially conducted to determine if there are longer fixations when an ambiguous word is inserted in a passage than when an unambiguous word is inserted in the same location. One group of subjects would read the passage with the ambiguous word in the critical locations and another group would read the passage with the unambiguous word. The computer would then be programmed to analyze the data. However, suppose that sometime later the experimenter became interested in frequency of fixation on words of different lengths, or frequency of fixation on words of different parts of speech, or frequency of fixation as a function of the serial position of the word in a sentence. If the data are stored on a disk, the experimenter can simply write new programs that will analyze the data in appropriate ways.

Greater Accuracy in Identifying the Location of the Fixation

One difficulty with eye movement recorders that are not on-line is that the accuracy of many systems is in the range of ±1 deg. With the exception of the contact lens method of recording and the double Purkinje image eye tracker, almost all of the recording devices reviewed by Young and Sheena (1975) are accurate to within only 1 or 2 deg of resolution. However, the resolution of many of these recording devices can be significantly increased by using the computer in a calibration routine. For example, the Biometrics Model 200 has a horizontal accuracy of 1 deg. However, by using the computer to calibrate the subject's eye position, resolution of .25 deg can be obtained in the horizontal plane. The most appropriate way of calibrating is done after the recording system has been adjusted for the subject; a dot pattern is presented (e.g., a 5 by 5 matrix of dots) and the subject fixates on each dot and pushes a button while looking directly at the target. The computer then samples the eye position signal and stores a value in a calibration table that is later used in translating from eye recording system voltage levels to display locations. While most experimenters have utilized a cathode-ray tube (CRT) to display the stimuli and the calibration pattern (McConkie et al., 1978; Reder, 1973; Vaughan, 1975), in principle there is no reason why such calibration techniques require the use of a CRT so that stimuli can be presented in alternative ways.

One of the major difficulties in scoring eye movement data is that there are often microsaccades and drifts of the eye. These oculomotor activities result in considerable difficulty for hand scoring. If the sampling rate of the experimenter is limited by the recording system (e.g., he or she can only sample every 16 or 32 msec, as in video systems), these small movements or deviations of the eye may be problematical or go undetected. However, with on-line recording and a sampling rate of every 1 msec, the problems can be minimized. That is, various experimenters note that a certain percentage of the data has to be eliminated because of drifts of the eye that make it difficult to determine the point of fixation, or because of other artifacts such as blinks. Frequent sampling of the eye movement recording system (i.e., every 1 msec) makes it possible to identify these small movements of the eye. One efficient strategy for dealing with these movements (unless they are the topic under investigation) is to combine the fixation with the drift or microsaccade. For example, in reading there are often fixations on adjacent characters in which one of the fixations is in the normal range of eye fixations in reading (e.g., 150-500 msec), but the other is considerably shorter. Some researchers have adopted the strategy of combining fixations that show this characteristic. On the other hand, data collected by Cunitz and Steinman (1969), Engel (1977), and McConkie (1979) indicate that microsaccades may represent important indications of cognitive activities, in which case it would be useful to have information about these small eye movements.

Greater Accuracy in Determining Fixation Duration and Saccade Duration

One of the major problems in eye movement research for some investigators is determining when a fixation occurs. Part of this issue is related to the problem described above that there are small movements of the eye. In reality, of course, the eye is never really still during a fixation. However, the facts that there are drifts of the eye during fixation and that there are microsaccades have resulted in some investigators arguing that fixation duration is a meaningless term. Hence, it is often suggested that "time on target" might be a more appropriate measure. Thus, in a reading situation, the experimenter would use the amount of time that the subject's gaze was on a particular word; in a picture-viewing situation, the amount of time that a particular object was looked at would be measured. Time on target then represents the total amount of time the subject's gaze is on the target, and the intervening activity of the eye (saccades, drifts, or microsaccades) is irrelevant. While such a strategy clearly overcomes the problems of identifying and defining a fixation, it also introduces other problems. For example, important cognitive events could be marked by the occurrence of an eye movement, and simple time on target does not take into account intervening eye movements away from and then back to the target. This problem can be circumvented quite easily by measuring time on target prior to an eye movement away from the target. Thus, if the subject makes two or three fixations on a long word (or an object in the picture-viewing case) and then makes an eye movement to another word, the measure is the amount of time on the word prior to the eye movement away from the word. On the other hand, if microsaccades represent something useful about cognitive activities, it is especially important for investigators to have this information and not to compress it into a more gross measure.

To return to the issue of identifying fixations, it is also true that an eye movement reaches peak velocity about halfway through the movement and gradually declines until the target is reached. However, the point at which the saccade ends and the fixation begins probably does not exist as a clear point of demarcation. As McConkie et al. (1978) pointed out, the actual point at which a saccade can be said to terminate is buried in a phenomenon sometimes referred to as overshoot. That is, at the end of the saccade, there is still movement associated with the eye settling into position after the force applied by the ocular muscles that triggered the saccade. Thus, the information about where the eye is centered is not available until sometime after the fixation has begun (about 30 msec or so into the fixation, according to McConkie et al.) and the point at which the saccade ended remains in doubt. However, McConkie et al. (1978) point out that these problems are not great; since regularities can be observed, the problems can be compensated for in the computer algorithms. Thus, given all of the potential problems associated with identifying the end of a saccade and the beginning of a fixation and with identifying the location of the fixation given the small movements of the eye, it appears that the most efficient strategy is to record eye movements on-line with a frequent sampling rate (e.g., every 1-2 msec). By sampling every 1 msec and comparing the present X-Y values with X-Y values obtained at some earlier point (say 4 or 5 msec earlier), a saccade can be identified if the values differ by a certain amount. If the values do not differ by the set amount, the subject is still fixated. When the saccade is identified, the termination of the eye movement and the beginning of the fixation can be determined in a similar manner. However, as indicated above, there are problems with identifying the end of the saccade and the beginning of the fixation, and if precise times about saccade duration and fixation duration are required, a strategy of defining saccades in terms of velocity of movement can be used (see McConkie et al., 1978, for a discussion of this issue). Of course, frequent sampling of the eye and the strategies described here result in a great deal of data being collected. While such data collection rapidly takes up disk space, the advantage is that the experimenter has rather complete records of eye activity. The experimenter can then develop algorithms for data reduction that seem most appropriate for the constraints of the experiment. At that point, for example, the experimenter may wish to combine fixations that fall on adjacent character positions within reading or that fall on a very circumscribed portion of a picture. Of course, this brings us back to the point made earlier: When eye movement data are collected on-line, the experimenter is able to reanalyze the data at different times according to different criteria.

Controlling Stimulus Presentation as a Function of Eye Location

While all of the advantages of recording eye movements on-line discussed above are important, the capability of controlling stimulus presentations as a function of eye location probably has the greatest potential for leading to advances in knowledge in cognitive psychology. Using this approach, eye movement behavior is monitored every 1 msec or so, and changes in the visual display that the subject is looking at are made contingent on the position of the eye. Techniques for conducting this type of research have been described by McConkie et al. (1978) and Reder (1973); studies reported by McConkie and Rayner (1975), Miller and Festinger (1977), Rayner (1975), and Rayner, McConkie, and Ehrlich (1978) have utilized these techniques. The capability of controlling stimulus presentation as a function of eye position gives the experimenter control of the stimulus in ways that were never before possible in situations that could be termed reasonably ecologically valid. This point will not be expanded upon here, but later in this paper more specific examples are given and the strengths of the technique are stressed.

AN ON-LINE EYE MOVEMENT RECORDING SYSTEM

The cognitive processes laboratory at the University of Massachusetts is currently equipped with two eye movement recording systems that are interfaced with a Hewlett-Packard 2100 computer. The computer and the experimenters' terminal are located in one room and the two eye movement recording systems are housed in separate adjoining rooms. In one room is a Biometrics Model 200 eye tracker that is interfaced through an A/D converter to the computer. A Hewlett-Packard 1300A CRT is interfaced with the computer and is used to present stimuli. The CRT has a P-31 phosphor and software for upper- and lowercase alphanumeric displays. Subjects are seated in front of the CRT, and a bite bar or chinrest (depending on the experiment) is used to stabilize the head. We have a general calibration pattern that consists of 3 by 3 or 5 by 5 dot matrices, and subjects are asked to fixate each dot and push a button as they do. These values are stored in the computer and are used in translating from eye recording voltage levels to display locations. Our work with this system has indicated that we are accurate to .25 deg or one character position with software calibration techniques when subjects read text displayed on the CRT. However, we have found a considerable amount of cross-talk in the horizontal and vertical voltages as the subject fixates target dots on a horizontal plane as the eyes move from the top row of dots (displayed near the top of the CRT) to the bottom row. In addition, the horizontal voltage is not invariant with changes in the vertical plane due to the curvature of the eye and the fact that the curvature changes relative to the position of the eye sensors as the subject moves the eye from the top of the CRT to the bottom. The vertical resolution of the eye sensors is rather poor since recording is from the eyelid rather than the iris-sclera boundary.[1] The vertical signal appears to be of little use in determining precisely where the subject is fixated. Thus, we ignore the signal from the vertical channel and record only from the horizontal and present the calibration pattern and stimuli in a rather restricted range of the vertical axis (corresponding to approximately three lines of text). Because there is a substantial lag (16 msec) in transmitting the signal from the sensors to the computer (unless a filter in the sensors is removed or disengaged and its function assumed by software routines), we use this system in conjunction with recording eye movements on a static display. The system is currently being used in some reading experiments in which display changes do not occur, three lines of text are presented simultaneously, and the subject advances the lines by pushing a button.

In the adjacent room, there is an Imlach PDS-1 CRT (P-4 phosphor) and a Stanford Research Institute double Purkinje eye tracker that is interfaced with the computer. Of course, the HP 1300A CRT can easily be moved into the room. The eye tracker records eye position from the reflection of the first and fourth Purkinje images and has the reputation of being highly accurate (resolution in minutes of arc) in both the horizontal and vertical dimensions. It is our intention to use this system to conduct studies in which display changes on the CRT occur as a function of the location of the gaze. When we have completed reliability tests of the system and other preliminary work, the signal from the eye movement recording system will be sampled every 1 msec, and display changes will occur at specific points on the CRT with respect to the position of the eye.

EYE MOVEMENT RESEARCH AND COGNITIVE ACTIVITIES

In this section, various types of research using on-line recording systems are described, including examples of research using eye movement contingent and noncontingent displays.[2]

Reading

One area of research that has received considerable attention because of increased sophistication of eye movement recording systems is reading. Studies in which subjects read connected discourse (McConkie & Rayner, 1975, 1976; Rayner, 1975) have utilized the technique of controlling the amount of text available to the subject and making display changes contingent upon the location of the gaze. In these studies, we have found that different types of information are obtained from different regions of the perceptual span, with meaning obtained from a relatively small region around the fixation point and more gross types of information (beginning letters of words, word shape, and word length) acquired from parafoveal vision. In future studies of this type, we intend to totally mutilate the foveal information so that the only usable information the reader has available is from eccentric vision. The general technique (Rayner, 1975) of changing single words at various locations in the text with respect to eye position also has great potential in investigating a number of interesting questions related to perceptual processing during reading.

In other studies involving noncontingent displays, we (Rayner, in press; Rayner & McConkie, 1976) examined characteristics of saccades and fixation durations in reading. Results of these studies indicated no correlation between the length of a saccade and the following fixation or vice versa and no correlation between successive saccades and successive fixations. One can easily imagine that when a reader makes a short saccade, there will be a longer fixation because he or she is having difficulty processing the text. On the other hand, short saccades could be followed by short fixations because the distance covered by the eye is relatively small and there is not as much new information to absorb as when a longer saccade is made. In fact, if the reader made a short saccade (1-4 characters), medium-length saccade (5-9 characters), fairly long saccade (10-15 characters), or very long saccade (16-20 characters), the most probable resulting fixation time was about 200-250 msec, although shorter and longer fixation times also occur for all of these saccades. Likewise, the most probable saccade length following a prior movement of the four types noted above was eight to nine character spaces.

The general finding that there is no correlation between these various characteristics of eye movements in reading has led us (Rayner & McConkie, 1976) to conclude that fixation time and saccade length represent independent aspects of eye behavior and that decisions about where to send the eye next are made independently of how long to leave it in one position. In addition, the probability of fixating a letter within a word of a given length is a linear function of word length; the probability of fixating on a letter within a word of a given length is represented by a curvilinear function. Also, histograms of fixation frequency on letter positions within words of various lengths do not show a flat function, but rather are peaked so that the largest percentage of fixations fall near the middle of words of various lengths. As word length increases, there is a tendency for fixations to fall slightly further toward the beginning of the word. On the basis of these and other data, we conclude that eye guidance in reading is made on a nonrandom basis.

Finally, there have been a number of recent studies dealing with language processes involved in reading (Just & Carpenter, 1978; Rayner, 1977). In general, these studies have shown that certain grammatical or syntactic elements in text receive more and longer fixations than other such elements. While it is encouraging to see studies of this type, it is also a little bit surprising that more attempts to deal with characteristics of language processes (as opposed to perceptual processes) during reading have not been made. A number of classic problems in language processing research could be investigated in a naturalistic way using eye movement data. For example, the processing of ambiguous words and sentences could be investigated during reading in a rather direct manner. Most attempts to deal with this issue in speech perception require certain assumptions and inferences by the experimenter or involve the subject in a concurrent task (such as phoneme monitoring or click detection) while he or she is listening to sentences. The only assumption required in using eye movement data to investigate the issue would be that the location and duration of the fixation reflect the cognitive activities occurring at the time, an assumption that seems reasonable given prior research (see Rayner, 1978a, for a review).

Integrating Information Across Eye Movements

One of the issues that has been largely overlooked in perceptual and cognitive research related to such activities as reading and visual search is how information from successive fixations becomes integrated into a unitary perception. The reason is that a great deal of the research in these areas has sought to avoid the complexities involved by presenting stimuli tachistoscopically so as to simulate the information that might be acquired during a single fixation. Recently several studies (Rayner, 1978b, 1979; Rayner et al., 1978) have investigated what type of information acquired from a parafoveal word is integrated with the foveal information after the subject makes an eye movement to bring the parafoveal word into the fovea. In these studies, a word or letter string is initially displayed in parafoveal vision, and the subject makes an eye movement to this initially displayed stimulus. During the eye movement, the computer replaces the initially presented word or letter string with a word that the subject must name or categorize semantically or lexically. The similarity of the initially displayed stimulus to the stimulus the subject must respond to is varied, along with the distance that the initially displayed stimulus is presented from fixation, and reaction times are compared as a function of these two characteristics. There are striking differences. As the initially displayed stimulus is presented closer to fixation, the amount of facilitation from the parafoveal stimulus increases. The more similar the initially displayed stimulus is to the stimulus the subject must respond to, the faster are reaction times.

Initially, we (see Rayner, 1978b) assumed that the fact that the visual similarity of the parafoveal stimulus to the foveal stimulus decreased reaction times was due to the integration of visual information across eye movements. Thus, it was assumed that the subject obtained rather gross information from the parafoveal stimulus and stored this information in some type of a buffer. Then the information in the buffer was combined with the new information in the fovea following an eye movement. To the extent that the parafoveal and foveal information were consistent, processing was facilitated; if the stored parafoveal information was inconsistent with the foveal information, processing was slowed. However, more recent experiments have indicated that this assumption is inadequate. We (Rayner, 1979; Rayner, McConkie, & Zola, Note 1) found that the case of the parafoveal word could be changed during the eye movement without disrupting the processing time, so that the same pattern of results emerged under these conditions in which case changes occurred and control conditions in which case changes did not occur. McConkie (1979; McConkie & Zola, Note 2) found similar results in a reading task. Thus, there is no evidence that the facilitation found in these experiments is due to subjects overlapping visual information across the two fixations. Rather, they seem to be doing some type of preliminary letter identification of the beginning letters of the parafoveal word, and this information facilitates the response to the foveal word.

Eccentric Vision

The type of experiments described in the preceding section deal not only with integrating information across fixations, but also with the type of information obtained from parafoveal vision, and the technique of changing the display during the eye movement seems ideal for determining the characteristics of the type of information it is possible for subjects to obtain from eccentric vision. If the visual field is divided into foveal vision, parafoveal vision, and the periphery, it appears that there could well be tradeoffs in terms of speed of identifying objects between holding fixation, making an eye movement, or turning the head. Sanders (1963), for example, has shown that with very large and simple stimuli, subjects can make discriminative judgments with good accuracy without moving the eye if the stimulus is less than 30 deg from fixation. Beyond 30 deg the eye must move to accurately make the judgment, and beyond 80 deg the head must move. For words or letter strings, accuracy of identification drops off rapidly so that the probability of correctly identifying a letter embedded in the middle of a trigram drops from 100% in the fovea to approximately 20% at 5 deg (Bouma, 1978). Likewise, reaction time for correctly identifying a word presented at different eccentricities increases at the rate of about 140 msec/deg as the word is presented further from fixation (Bouma, 1978). However, it is unclear if there is a tradeoff for identifying words or other types of stimuli in parafoveal vision. For stimuli presented close to fixation, identification may be faster if the subject does not make an eye movement; for stimuli presented further from fixation, it may be faster (and certainly more accurate) to move the eyes. In a recent experiment (Rayner & Morrison, Note 3), we attempted to determine if there is a tradeoff point for identifying words. Subjects were asked to name words or make lexical decisions. Stimuli were presented various distances from fixation in parafoveal vision; in one condition subjects were allowed to make eye movements, while in another condition they maintained fixation. As would be expected, errors increased as the stimuli were presented further from fixation when eye movements were not allowed. In fact, in the lexical decision task, while accuracy was about 96% in the fovea, if the stimuli began (or ended, in the case of stimuli presented left of fixation) 1 deg away, subjects were correct only 75% of the time. When the stimuli were presented 5 deg from fixation, performance was at the chance level when eye movements were not made. Interestingly, it appears that a certain amount of processing is involved in holding fixation. In the eye movement condition, subjects were about 100 msec faster making responses to foveal stimuli than they were in the no eye movement condition. If we examine the slope of the reaction times for the two conditions, we find an increase of about 11 msec/deg for stimuli presented beyond 1 deg in the eye movement condition and a slope of about 35 msec/deg in the no eye movement condition. The data are based on total response time and thus include the reaction time of the eye in the eye movement condition.

In other research dealing with eye movements and eccentric vision (Rayner et al., 1978), attentional allocation was found to be related to the direction of the eye movement. Thus, the points where subjects direct their eyes in saccades must indicate the region from which they primarily acquire information prior to the eye movement.

Picture Processing and Visual Search

Recently, there has been a great deal of interest in investigating picture perception and visual search using eye movement data as dependent variables (e.g., Loftus & Mackworth, 1978; Parker, 1978; Rayner, 1978a). Generally, the research has involved the use of noncontingent displays as subjects look at static scenes. One of the major conclusions reached is that information in nonfoveal vision is used to guide the eye to informative areas. However, this conclusion is merely implied in the research, and there have not been any direct manipulations of the extent to which such nonfoveal vision is the source of eye guidance. It now seems possible for researchers to present graphics displays of line drawings and to change the characteristics of certain objects as the subject makes an eye movement to that object; eye movement data are examined as a result of these types of display changes. Experiments using on-line recording systems that enable the experimenter to control the visual stimulus present on each fixation and to make display changes contingent on the eye position could provide important answers to many questions related to picture processing and visual search.

For example, not only could the characteristics of information obtained from nonfoveal vision be investigated, but issues related to how information is integrated across eye movements when looking at pictures could also be studied.

CONCLUDING COMMENTS

A number of advantages of using on-line computers to record eye movements in various cognitive processing tasks have been described, and illustrative examples of research using on-line recording have been discussed. The technique of controlling the characteristics of the stimulus present on any fixation or of changing the characteristics of the display contingent upon the location of the gaze represents an important new methodology for investigating certain cognitive and perceptual processes. However, it should be emphasized that eye movement research does not represent the alpha and omega in cognitive or visual information processing research. There are many activities that can be studied just as effectively using other techniques. Likewise, there is no reason why eye movement data should be obtained in certain tasks just to see what they look like. One of the reasons for the downfall of eye movement research in previous eras was that the resulting data were often used in trivial ways. Eye movement data have the potential to reveal important cognitive activities in certain situations, and wise use of eye movement techniques and data will go a long way to insure the success of the newest era of eye movement recording.

Of course, it is naive to believe there are no problems associated with research using on-line computer techniques to record eye movements. Anyone who has ever used a computer to collect data can generally catalog the potential hardware and software difficulties and problems that can be encountered. When the potential problems associated with rather delicate eye movement recording systems (such as the SRI double Purkinje eye tracker) are added to possible problems with the computer, the potential for encountering problems is greatly magnified. Loftus (1979) discusses some of these problems.

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NOTES

1. More reliable vertical resolution can be obtained by taping the subject's eyelids open and recording from the upper and lower iris-sclera boundaries.

2. The research by the author described in this section was conducted at the Massachusetts Institute of Technology, Cornell University, and the University of Rochester. The author would like to thank David Silver, Scott Outlaw, Leonard Zubkoff, Steven Hoffmann, and especially, George McConkie for valuable assistance in the computer programming involved in the research.