*Behavior Research Methods & Instrumentation*
*1974, Vol. 6 (6), 525-530*

# METHODS & DESIGNS

## High-speed data processing and unobtrusive monitoring of eye movements

ROBERT H. LAMBERT and RICHARD A. MONTY
*U.S. Army Human Engineering Laboratory*
*Aberdeen Proving Ground, Maryland 21005*

and

ROBERT J. HALL
*University of Nevada, Las Vegas, Nevada*

**A system has been developed that monitors eye movements without imposing any unnatural constraints or mechanical attachments on the subject. The system also features high-speed on-line data processing.**

When the range of eye behaviors are viewed in their entirety, it seems fair to say that the state-of-the-art of eye-movement recording is still in its infancy. At present, no single technique existing or under development can adequately record the entire range of eye-movement behavior without compromising or interfering with normal visual processes. Therefore, once the experimenter has defined his objective, he must look at tradeoffs between a method's accuracy and the extent to which it distorts and constrains the behavior he wishes to study (Hall & Cusack, 1972). For example, if the experimenter wishes to observe eye movements without inducing severe postural constraints or restricting head movement, he must be willing to sacrifice some degree of tracking accuracy. In many situations, however, lower accuracy can be compensated for by partitioning and distributing the stimulus situation under investigation.

The present paper describes an eye-movement camera or oculometer designed to overcome some of the inadequacies of earlier systems, many of which have been described by Young (1963) and Young and Sheena (1975). Specifically, the oculometer described here imposes no constraints on the subject that might interfere with comfort or normal viewing behavior; nor is it necessary that the subject be aware that his eyes are being monitored. In addition, the system measures a wide spectra of visual responses that include basic measures such as variability of fixation times and scan patterns, and provides a data-reduction capacity for handling large volumes of data with an on-line processing capability that provides immediate feedback to the experimenter or to the subject if desired.

This research may be reproduced in full or in part for any purpose of the United State Government. Most of the development of the instrumentation was done while the first and third authors were with the Special Projects Division, EG&G, Inc., Las Vegas, Nevada under contract for the U.S. Army Human Engineering Laboratory.

### SYSTEM CONFIGURATION

It is convenient to think of the oculometer as consisting not only of the hardware for monitoring the eyes and reducing the data, but also of the environment and the stimulus-projection room. Conceived of in this way, the system can be described as consisting of a viewing studio separated from a camera room by a rear-projection screen, and a control room, all shown in the artist's illustration of Figure 1 and represented in the functional block diagram of Figure 2.

#### The viewing studio

The subject is seated in an armchair located approximately 1.5 m in front of a polarized,

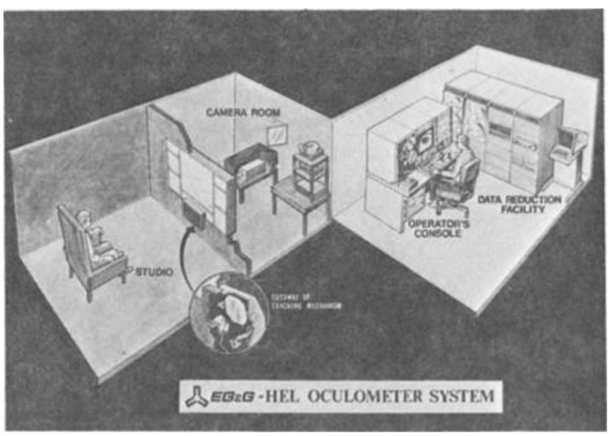


Figure 1. Artist's illustration of the laboratory.

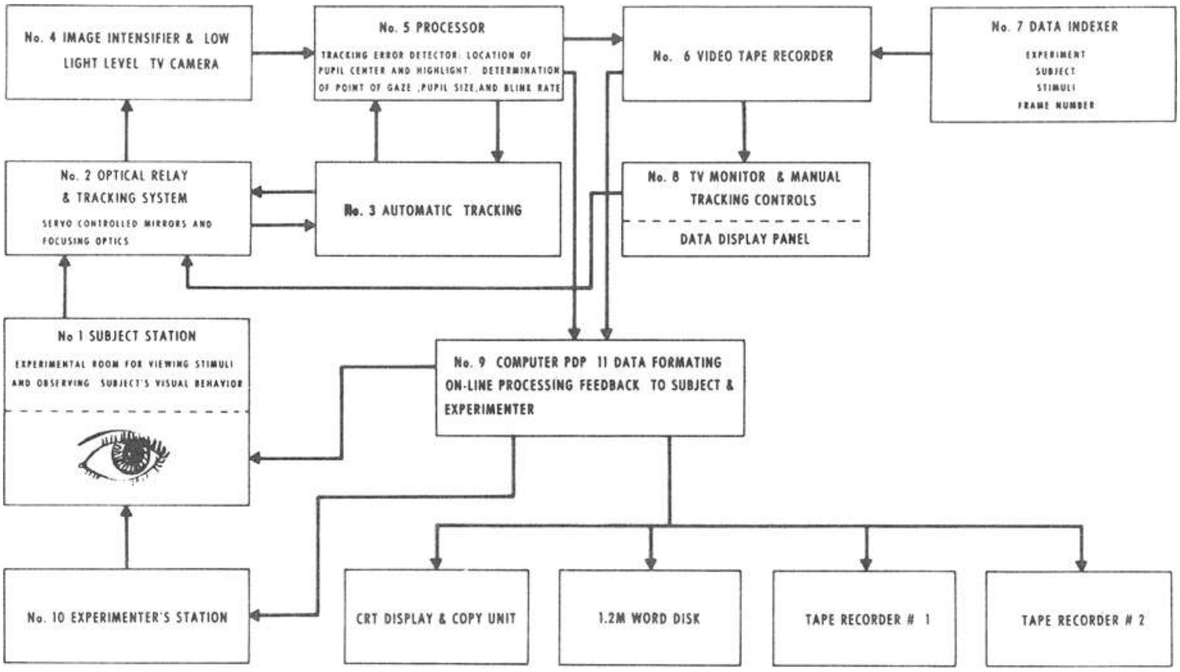


**Figure 2. Schematic representation of the system.**

rear-projection screen measuring approximately 1 m on a side as shown in Figure 3 and represented schematically by Block 1 of Figure 2. No constraints are imposed on the subject except that he remain seated. Generally speaking, as long as the subject's head remains within a space of approximately 1 cu ft, his eye movements are tracked automatically. Polarized lighting surrounds the viewing screen providing a comfortable level of room illumination as well as sufficient illumination to allow adequate TV viewing of the eye. The resulting ambient illumination of the subject ranges from 1 to 3 fc. Light from a small unpolarized section of the surround which is reflected by the front surface of the cornea is allowed to pass through the optical system, producing a bright spot (highlight) at the camera. It is the apparent position of this highlight relative to the center of the pupil that is directly related to eye orientation, or line of sight. The low-light-level TV camera (Westinghouse Model No. STV 614) is concealed in what appears to be a speaker box located directly beneath the screen.

## The camera room

The camera room houses a variety of devices used to present stimulus materials to the subject, such as Kodak Carousel or random-access projectors (Massey Dickinson Co, Inc., 9-11 Elm Street, Saxonville, Mass. 01701). It is possible to utilize other readily available devices such as motion-picture cameras or CRT projection devices. In addition, the camera room houses the concealed optical relay and tracking system (Block 2), the controller for automatic eye tracking (Block 3), and the TV camera (Block 4).

The optical relay and tracking system, along with its controller, performs two major functions. The first is one of relaying information to the TV camera. In this instance, the image of the eye and highlight go to the image intensifier and camera. The second function, tracking the movement of the eye, is performed automatically by a system of mirrors and lens-focusing mechanisms. These mechanisms keep the eye in focus within the field of the stationery TV camera. The control information for the servo-motors that track the eye

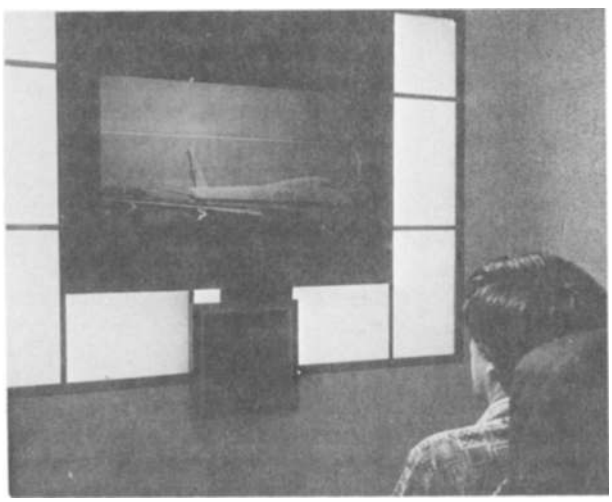

**Figure 3. Subject seated comfortably in the studio. The camera is concealed behind the speaker grill, and the highlight is generated by the bright spot between the grill and the screen.**

**Figure 4. The operator's console and the data-reduction facility. The CRT and hard-copy printer can be seen on the far right.**

comes from a processor (Block 5) which determines the location of the highlight and the location of the pupil. The relative position of the highlight and the pupil is used to determine point of gaze. A signal proportional to the position of the pupil is sent to the mirror-servos which continually maintain an image of the eye in the approximate center of the field of view of the camera.

**The control room**

The control room, shown in Figure 4, houses the electronic processor, experimenter console, data-reduction equipment, etc., as represented by Blocks 5-10 of Figure 2. The processor in Block 5 is essentially an analog computer housed in the experimenter's console. It computes point of gaze by determining the distance between the center of the pupil and the location of the highlight. This information is displayed on the data panel to the right of the TV monitor (Block 8), and it can also be recorded in digital form (Block 6) on the video tape recorder (Sony Model No. EV 200), shown on the left side of the operator's console. This last feature is particularly important from the experimenter's point of view–should the digital computer (Block 9), which normally processes the data on-line, be shut down for any reason, the experiment can still continue as the data can be stored indefinitely on the video tape for processing at a later time.

The experimenter sits at the console and views the pupil. The joy stick in front of him is used to superimpose a circular cursor on the image of the pupil, i.e., acquire the target. Once this is accomplished, the experimenter switches out of the manual mode and the automatic tracker assumes control and tracks the eye until the pupil is obscrued, in which case the target must be reacquired manually. Normally, tracking the pupil presents no problem, but the target can be lost if the subject sneezes, laughs violently, rubs his eyes, etc.

Also displayed on the upper right side of the console is information concerning S (i.e., his number), the stimulus or slide number, the frame number and the X-Y coordinates (Block 7). All of this information is either recorded on video tape, sent directly to the computer, or both.

Information concerning the eye's position and other behavior such as blinking and changes in pupil size can be fed to the Digital Equipment Corp (DEC) PDP 11/20 computer (Block 9), from either the electronic processor if real-time data processing is required, or from the video tape recorder if one wishes to process data from an earlier experiment. The computer, which interfaces with a DEC 1.2-million-word disk and two DEC industrial compatible tape decks, performs several functions. First, it processes the data in real time so that information (such as pattern of fixations) can be provided to the experimenter on the high-speed CRT computer terminal (Tektronix Model 4010-1). This information can also be fed directly to projection devices such as the random-access projector or a video projector in the event one wants to change the material being shown to the subject based on his previous performance. Secondly, it relays the processed raw data to one of the tape decks for storage and subsequent statistical or mathematical analysis. Thus, it is possible to go directly from calibration of the raw data to analysis of group data without any manual manipulation of that data. The same CRT terminal, together with its keyboard is used to program the computer with the sequence of events that constitutes an experiment. Finally, at any time, the CRT terminal can be used to provide a hard copy of graphics (scan patterns) or processed data, such as average fixation duration or frequency of fixations of a particular stimulus, on the Tektronix Inc. Hard Copy Unit (Model No. 4610).

## DEFINING A FIXATION

The basic data consist of the X and Y positions of each eye fixation and the duration of those fixations.

The program used to define a fixation operates like a complex filter, which determines: first, what data are usable (i.e., data that contain sufficient information to determine the eye position); and secondly, whether a sufficient number of frames are within the boundary conditions used to define a fixation. The shortest time used to define a fixation is six frames or 100 msec.

Data may be determined unusable for a variety of reasons such as (a) highlight loss (i.e., highlight is below the threshold set for defining its presence; for example, blinking produces highlight loss) (b) severe tracking error resulting from failure of the cursor used to outline and track the pupil to overlap the pupil exactly, (c) printing errors stemming from video noise, etc., and (d) gross head movements (e.g., laughing or sneezing) that may cause the camera to lose its view of the subject. When this happens, the tracking device is brought back into lock by the operator's manual override.

Continuous point-of-gaze measurements are partitioned into a temporal series of fixation coordinates with the aid of the complex filter program mentioned earlier. X and Y refer to the measured horizontal and vertical coordinates of the subject's point of gaze on the rear-projection screen. This program first collects a series of six measurements (representing a time span of 100 msec) and determines whether the standard deviations (in X and Y) are less than preselected allowable deviations and wehhter the computed mean values of these coordinates indicate that the group may logically be associated with the previously established fixation. If both conditions are satisfied, the program concludes that the onset of a fixation has been detected, and the spatial coordinates and starting times are recorded. As subsequent measurements are taken, X and Y values are subtracted from these coordinates, yielding $\Delta X$ and $\Delta Y$, respectively. Whether the new data should be interpreted as a continuation of the established fixation or the possible initiation of the next fixation is determined as follows: if the absolute values of $\Delta X$ and $\Delta Y$ are less than preset values (boundary conditions) the fixation time is extended accordingly. If not, the program will continue this test until a total of four sequential measurements fail to meet the boundary condition criteria. Any data point measured during this sequence which falls within the acceptance boundaries automatically extends the fixation to that point in time and the test reinitiated with the following measurement. If the average of four sequential measurements, which are individually rejected, lies within the same boundaries, the fixation time is again extended and testing reinitiated as before. Failing this, two additional measurements are taken and the standard deviation of the six collected values is computed. The six stored data points are then systematically replaced by incoming measurements until the standard deviation of the group becomes sufficiently small to indicate that a new fixation has been detected.

## CALIBRATING THE SYSTEM

Two techniques have been effectively utilized to gather calibration data when the subject first enters the studio, without alerting him to the fact that his eyes are being monitored. Both techniques are performed under the guise that the experimenter is making sure that the projection devices are properly focused. The first technique consists of projecting Landolt Cs in the corners and center of the viewing screen and having the subject systematically scan the Cs and report the position of the opening. The second technique requires the subject to view a Troxler calibration slide which projects a dark background with four dots, one in each corner of the viewing screen. This task provides excellent calibration data, since the disappearance and fading of the dots in the peripheral position of the visual field is a very real phenomenon known as the Troxler effect (Troxler, 1804). The subject is instructed to stare at one particular colored dot and then to report the disappearance or change in any of the other three. This procedure is repeated for each of the dots in the four corners of the screen. Either procedure can be completed in a matter of seconds.

## STATISTICAL ANALYSIS

It is possible to go directly from monitoring of the subject's eye movements to statistical analysis of group data without manual manipulation of the data. A single subject's data is readied for analysis on a given criterion (such as number of fixations, average duration of fixations, etc.) as it is collected and stored on the magnetic tape unit until all subjects in the experiment have been tested. The 24K of core allows for a reasonably sophisticated degree of processing. A popular program has been the analysis of variance developed by Butler, Kamlet, and Monty (1969) which enables any combination of up to eight within and eight between variables to be assessed. Results of these analyses are similarly displayed on the CRT and hard-copies produced on the printer when desired.

## APPLICATIONS

The potential applications of the system are numerous. Any material that can be projected on a rear-projection screen can be displayed. In addition, modification of the stimulus display can be directly contingent upon the subject's preceding visual or motor responses. Further, the on-line capability can easily be used to simultaneously collect data on physiological parameters such as heart rate, EEG, etc., as well as data on motor responses such as reaction time.

To date, the system has been used to study a variety of problems. For example, Hall, Rosenberger, and Monty (1974) compared the eye movements of heroin addicts and matched controls engaged in word and object recognition tasks. Representative data are shown in Figure 5. While there was little difference in the average duration of fixations for addicts with old objects (i.e., objects they had seen earlier in the test session), regardless of whether they were looking at drug-related objects or neutral objects, in all other cases (i.e., with objects seen for the first time or with the nonaddicted subjects) drug objects led to more fixations than neutral objects. These differences were attributed to motivational or interest factors associated with the importance of the material shown and basic differences

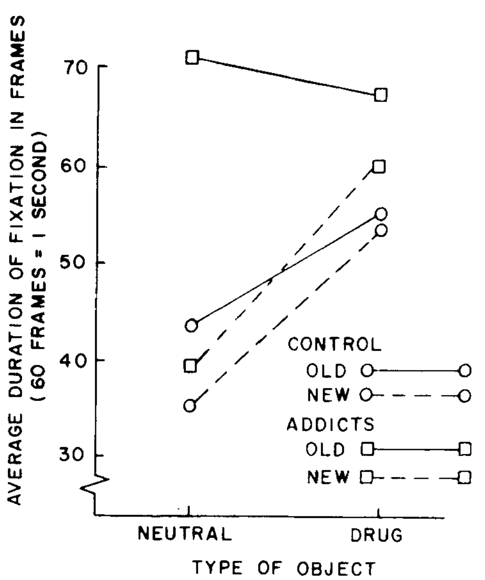


**Figure 5. Average duration of fixation of heroin addicts and matched controls engaged in an object-recognition task (After Hall, Rosenberger, & Monty, 1974).**

in psychological and central nervous system processes that regulate eye movement. The series of studies indicated that addiction may lead to an altered sensory capacity in the temporal domain associated with the gating and subsequent scanning of stimuli.

A different application of the oculometer system involved examining eye movements during a simple detection and threat-evaluation task (Hall, 1974). The objective was to select a representative problem that would demonstrate how the oculometer system might contribute to display research. A 75-min display task was devised that involved surveillance, tracking, and threat evaluation. During this task, the amount of eye-movement data generated and analyzed for a single subject was 270,000 frames, or a total of 2,970,000 frames for all 11 subjects. The analysis of mean distance between successive fixations and mean fixation durations provided no indication of fatigue or impaired performance over time. However, fixation durations were highly uniform during search periods when no targets were present and highly variable when the subject was observing and evaluating a target.

More recently Fisher (1974) has utilized the system in studies of reading and search behavior with children and adults. In a typical experiment, subjects view printed text projected with a computer-controlled random-access slide projector. Sometimes the text is normal; at other times it may be perturbed by eliminating spaces between words, alternating type, etc. The subjects are asked to read as quickly and accurately as possible (reading condition) or to search for a target word embedded in the text (search condition). Representative adult data are shown in Table 1. When reading and searching normal text, fixation durations are about the same. When the text is perturbed, reading fixations increase in duration dramatically while search-fixation durations increase only slightly. Likewise, reading speed decreases more dramatically when the text is perturbed than does search speed. Further, perceptual span (character spaces per fixation) is smaller for reading than search and decreases further in both tasks when spatial cues are perturbed. This indicates that reading requires more fixations because less information is absorbed on each fixation than during search. In short, these data show that both task demands, e.g., comprehension and spatial factors, can reduce the functional visual field of view.

## LIMITATIONS AND ADVANTAGES OF THE SYSTEM

The advantages of the system are clear. First and foremost, unlike earlier systems, it does not interfere with or restrict the subject's visual behavior. The extent to which other systems do may now be determined objectively by comparing a subject's performances on two or more systems. Second, it is unnecessary to call the subject's attention to the fact that his eye movements are of interest; thus problems of self consciousness, etc., can be avoided. Third, the system can handle voluminous quantities of data in real time. A million frames of data can be reduced for statistical analysis of a given criterion in less than 4 h, a task which if performed manually or even semimanually, would take months. And finally, when studying reading or search, each fixation can be identified by location and duration so that progressive and regressive saccades are easily discernible.

The principal drawback of the system is its initial cost, but cost is directly dependent upon the sophistication of the data-reduction capabilities desired. A complete system such as the one described here would cost at least $100,000 if purchased commercially. Of course, the time saved quickly compensates for the

**Table 1**
**Representative Data of Adult Subjects Engaged in Reading and Search (After Fisher, 1974)**

| | Normal Case/ Normal Space | | Alternating Case/ No Space | |
|---|---|---|---|---|
| | Reading | Search | Reading | Search |
| Rate (Words Per Minute) | 180 | 256 | 36 | 148 |
| Fixation Duration (in Milliseconds) | 266 | 260 | 417 | 310 |
| Words (Read or Searched) | 66 | 47 | 116 | 59 |
| Words Per Fixation | 1.05 | 1.9 | .27 | 1.00 |
| Character Spaces (Read or Searched) | 351 | 270 | 511 | 260 |
| Character Spaces Per Fixation | 5.6 | 11.8 | 1.2 | 4.4 |

initial investment. A second limitation is the system's monitoring accuracy, which is a direct result of not restraining the subject's head movements in any dimension. Currently, the system can perform with approximately 2 deg of positioning accuracy, but this could probably be improved with modification of the system software. Further, the system does not track well with individuals wearing glasses or with subjects who have low-contrast pupils. Poor tracking results in the loss of data. Solutions to these two problems are well within the state of the art, and are currently under development.

## REFERENCES


Butler, D. H., Kamlet, A. S., & Monty, R. A. A multi-purpose analysis of variance FORTRAN IV computer program. Psychonomic Monograph Supplements, 1969, 2, 301-319 (whole No. 32).

Fisher, D. F. Spatial factors in reading and search: The case for space. Paper presented at a Specialists' Meeting on Eye Movements and Psychological Processes, Princeton, New Jersey, 1974.

Hall, R. J. Eye movement fixations and gating processes. Paper presented at a Specialists' Meeting on Eye Movements and Psychological Processes, Princeton, New Jersey, 1974.

Hall, R. J., & Cusack, B. L. The measurement of eye behavior: critical and selected reviews of voluntary eye movements and blinking. Tech Memo 18-72, U.S. Army Human Engineering Laboratory, Aberdeen Proving Ground, Maryland, 1972.

Hall, R. J., Rosenberger, M. A., & Monty, R. A. An experimental investigation of the visual behavior of young heroin addicts and matched controls. JSAS Catalog of Selected Documents in Psychology, 1974, 4, 7.

Troxler, D. Über das verschwinden gagebener gegenstande innerhalb unsers gesichtskreises. In K. Himly and J. A. Schmidt (Eds.), *Opthalmologische Bibliothek* 1804, 2, 51-53.

Young, L. R. Measuring eye movements. American Journal of Medical Electronics, 1963, 2, 300-307.

Young, L. R., & Sheena, D. Survey of eye movement recording techniques. Behavior Research Methods & Instrumention, 1975, in press.


(Received for publication August 29, 1974; revision received October 3, 1974.)