On-line, real-time recording of eye orientation using the corneal reflection method

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The orientation of a subject's eyes can be automatically sampled in real time at 60 Hz using Mackworth's corneal reflection method, a closed circuit TV system with a brightness-amplitude trigger, and a minicomputer. The organization of the electronic interface and software (for recording and behavioral control) is described, along with the characteristics of the recording system and potential sources of artifact. Sample calibration and experimental data are presented.

The investigation of eye movements by television recording of the corneal reflection of a light source (Mackworth & Mackworth, 1958; Mackworth & Thomas, 1962) has been used by a number of investigators in studies of visual search and discrimination learning (e.g., Gould & Schaffer, 1965; Loftus, 1972). Manual frame-by-frame analysis and scoring of videotaped or filmed records is time-consuming and introduces the possibility of error. This paper describes a method for automatically recording the location of the reflected source image in such experiments.¹ The system described here has been in almost daily use since 1969 in studies of monkeys' visual discrimination learning at the Primate Behavior Laboratory of Brown University (see Schrier & Wing, 1973; Vaughan, 1970).²

HARDWARE ORGANIZATION

System operation is shown in Figure 1. The corneally reflected image of a light source is recorded by a closed circuit TV camera modified so that the horizontal and vertical sawtooth voltages (both 1 V p-p) of the TV scan are accessible externally.³ A Schmitt trigger senses the brightness level of the composite video output of the TV

camera, with the trigger threshold adjusted to detect the image. The position of the image on each TV scan is recorded as follows: At the beginning of the scan, an R-S flip-flop (the "flag") is reset by the computer. When the TV scan crosses the image the video signal exceeds the Schmitt trigger threshold, and the flag is set. The flag is sensed, in turn, by the computer, using a skip instruction. Software then records the vertical and horizontal scan positions of the image, using two analog-to-digital converter channels. If no image is detected in the first 10 msec of the TV scan, the absence of a fixation is recorded (thus, the recording field is limited to the top two thirds of the TV scan). Because of the high frequency of the horizontal scan, it is necessary to retain the voltage present at the instant that the flag is set, using a sample-and-hold amplifier, until it can be sampled by the analog-to-digital converter. Otherwise, the software delay in sampling the horizontal voltage would permit a substantial error in the horizontal position recorded. The sample-and-hold amplifier is controlled by the flag.

BEHAVIORAL CONTROL

The behavioral contingencies of the experiment are

Figure 1. Schematic diagram of the TV-computer interface, showing the recording of the image for two TV scans. For clarity, a six-line TV scan is shown; actually the scan has about 200 lines, and the image is 10-12 lines wide.

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Figure 2. Overall system organization.

also computer controlled. Each trial consists of two phases: a calibration phase in which the subject is required to stare at a fixation point while spatial adjustment of the recording system is checked, and a discrimination phase in which the subject's fixations are recorded while it makes a two-choice discrimination response.

Calibration is maintained by presenting a tone cue at the beginning of a trial and a dimly illuminated spot on the lower of three keys on the response panel (Figure 2). The subject fixates this spot (fixation must be stationary with 3 deg of visual angle from one TV scan to the next) for a period of 1-2 sec. When such a fixation has occurred, the spot intensity is briefly increased, and the subject may press the key to initiate the discrimination phase of the trial. On the basis of the location recorded for this fixation, the program may give the experimenter auditory warning that the calibration requires adjustment, which is most easily done by modification of program parameters through the computer's analog input potentiometers. Except for the beginning of an experimental session, this sort of readjustment is required infrequently.

During the discrimination phase of a trial, one pattern stimulus is generated on each of the upper discriminative keys on the response panel and a choice response permitted. Correct choices are reinforced with banana pellets. Codes representing keypress responses and other behavioral data are interleaved with the fixation location data in a data buffer.

At the beginning of each intertrial interval, if the amount of data in the data buffer exceeds the capacity of a tape block, data are written onto magnetic tape.

SOFTWARE ORGANIZATION AND TIMING

The software is arranged as two quasi-independent programs run in rapid alternation.⁴ The foreground program controls the behavioral experiment by enabling the display of stimuli on the stimulus CRO, specifying timing intervals, and evaluating responses when they occur. The background program records the location of

the fixation every 1/60 sec in synchrony with the TV scan. The first 10 msec of each scan are dedicated to determining the location of the image, as described above. Fixation and location data are recorded in the data buffer as a sequence of vertical and horizontal coordinate pairs, each representing one TV scan (16.6 ... msec) normalized in terms of a 16 by 16 matrix corresponding to the response panel. After every TV scan, a simulated image is displayed on a second CRO (Figure 2) for evaluation and comparison with the TV monitor, along with summary data during the intertrial interval. On request from the foreground program, through shared software switches, data may be discarded or retained in the data buffer, or the subject's stimulus display may be refreshed. Finally, control is returned to the foreground program at the end of a TV scan if a behavioral event (elapsed time, keypress, or, in some experiments, fixation on a particular stimulus key) requires behavioral control. In no case, except during the intertrial interval, do these tasks require more than 6 msec of processing time, so that no TV scans are missed.

SPATIAL CALIBRATION, ACCURACY AND ARTIFACTS

Figure 3 indicates the location of fixations recorded (using a procedure similar to that of the calibration phase, above) as a single stimulus is moved in 1.6 deg steps horizontally or vertically. A dimly illuminated

Figure 3. Recorded fixation location as a function of the position of a single, fixated stimulus. Vertical bars indicate the range of locations observed.

point stimulus brightens briefly if the subject fixates it for a 1-2-sec period, and responses to the stimulus are reinforced. In this case, several trials are run at each point, then the stimulus is moved to a new position. Both horizontal and vertical linearity is good over a 20-deg range. The vertical and horizontal directions differ somewhat (cf. Mackworth & Thomas, 1962) in scale and variability. Several artifacts may contribute to this difference. First, corneal reflection methods are extremely sensitive to head movements: A .075-mm head movement results in an apparent 1 deg eye movement (Mackworth & Mackworth, 1958), and the head fixation method used in obtaining these data (see Schrier, Povar, & Vaughan, 1970) did not control vertical movements as well as currently used restraints (Freindlich, 1973). Second, Gould and Schaffer (1965, Appendix) report that the vertical and horizontal curvatures of the cornea differ; such differences obviously affect the recording scale. Third, the scale of the recording system changes with the placement of the source light and the TV camera lens, and with the angle that these subtend at the corneal surface (this is not a factor in the data of Figure 3, since these were obtained in a single session). If the position of these relative to the eye cannot be maintained from session to session, the distortion of the visual field in the recorded data will vary. Within these limitations, the system discriminates perfectly between fixations directed at stimuli separated by 15 deg of visual angle (Figure 4) and would do so even if the stimuli were much closer together.

TEMPORAL CALIBRATION AND ARTIFACTS

Methods that use a Vidicon type TV camera are affected by the time constants of the Vidicon tube and by the discontinuity inherent in the sampling of the TV system. To measure this effect, a fixation was simulated by interposing a photographic shutter between the source light and an artificial glass cornea. Both the pulse of light thus cast on the cornea and the TV monitor output were recorded with phototransistors, and the two were compared on a dual-beam storage oscilloscope (Figure 5). A change in the video output of the TV monitor lags from 15-30 msec behind the change in the "position" of the eye. At normally used brightness levels, these time lags are symmetrical, so that the fixation duration is recorded accurately (though it lags

HORIZONTAL FIXATION POSITION

	1	2	3	4	5	6	7	8	9	10	11	12	13	14
VERTICAL FIXATION POSITION														
4														
5			1											
6		1	15	3								13	9	
7		1	7	3	1							6	8	
8														
9														
10								1						
11							6	9	1					
12							2	7	1					
13														

Figure 4. Percentage of fixations recorded in each cell of the data matrix corresponding to the response panel during a session of about 300 discrimination trials (fixations during the discrimination phase only). The three concentrations of fixations represent the left, center and right keys, which were separated by 15 deg. The keys subtended a visual angle of 4 deg, and the stimuli themselves about 1 deg. Percentages less than .5 omitted. The fixations of the calibration phase typically fell within one of two vertically adjacent cells of the data matrix (e.g., Coordinates 8, 11 and 8, 12).

in time). This lag may be a problem if an experiment requires accurate recording of the beginning or end of a fixation, as in the measurement of oculomotor reaction time, the duration of individual saccades, or other saccade-dependent procedures (e.g., Reder, 1973). Since the lag is inherent in the Vidicon tube, it is present whether an automated, or videotape/film system is used.

CONCLUSION

The real-time recording of eye orientation using an on-line adaptation of Mackworth's corneal reflection method accurately records the direction and duration of fixations within ± 1 deg of visual angle and ± 20 msec when head-restrained monkeys serve as subjects. Similar accuracy might be obtained with human subjects if small head movements are adequately restricted.

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Figure 5. Idealized response of the system to a single simulated fixation.

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NOTES

1. An earlier version of the present system has been previously described (Schrier, Povar, & Vaughan, 1970). A similar system has been developed independently by Buchsbaum, Bryan, Pfefferman, Carmen, & Stillman (1973).
2. While the work described here involved monkeys, the

method is equally applicable to work with humans. In either case, restriction of head movements, as with a bite bar, is required.

3. Since the TV system, in effect, samples the image at 60 Hz, the computer program must operate in synchrony with the TV scan. This is accomplished by the program's sampling the vertical scan position voltage. The modified CCTV camera and Schmitt trigger were obtained from Massey-Dickenson Company, Inc., Saxonville, Mass. The interface, constructed with R- and A-series negative-logic modules, was attached to a LINC-8 computer (Digital Equipment Corporation, Maynard, Mass.). The system is described here in general terms; another logic system (e.g., TTL) might be more appropriate for other computers. Logic and point-to-point wiring diagrams of the interface may be obtained from the author.

4. The program was written in LINC assembly language using the COMMAND system (similar to DIAL). The behavioral program transfers control to the background program using a subroutine call, with multiple arguments that denote an appropriate transfer within the foreground program if any key (left, center, or right) is pressed, or if a specified time interval expires. A definition of such a control state requires five to seven words of memory. The eye-movement recording of the background program is invisible (except for a few shared software switches) to the foreground program. This allows many different behavioral programs to be written in a similar syntax without consideration of the details of operation of the background program. Using this syntax, very complex behavioral procedures may be written in the 1000₈ words of core allocated for the foreground program. The background program (1000₈ words), I/O subroutines for the Teletype and magnetic tape (2000₈ words), the data buffer (2000₈ words), and PROGOFOP (the LINC-8 operating program—2000₈ words) occupy the remainder of the 4K core.