Behavior Research Methods & Instrumentation
1981, Vol. 13 (1), 20-24

An automated eye movement recording system for use with human infants

LOUISE HAINLINE
Brooklyn College, City University of New York, Brooklyn, New York 11210

An infrared corneal reflection eye movement system modified for work with human infants is described. The system generates on-line digital information on eye position at a sampling rate that allows examination of the temporal and spatial characteristics of fixations and eye movements. An algorithm for defining fixation and eye movement episodes is described.

There has been much speculation and research on the development of perception in infants, in part because it represents the roots of adult perception. Because the information gleaned from visual exploration appears to be crucial for cognitive and social development, psychologists have been interested in developmental changes in the visual scanning of infants viewing visual forms. There exist a number of different optical methods of measuring "direction of regard" or the location in space toward which the eye is pointed (Young & Sheena, 1975). Some of these methods have accuracies of minutes of arc, but most of the very precise techniques require rigid immobilization of the head, and frequently, they require that the subject wear some part of the eye movement recording apparatus on the head near the eyes. For work with infants, who will not readily tolerate passive restraint and whose natural curiosity appears to mandate that they look at almost everything in an experimental setting except the stimuli designated by the experimenter, such coercive and obtrusive measures are clearly inappropriate.

There have been some successful attempts to collect data on scanning from infants, primarily in the newborn period, by using some variant of the corneal reflection method (e.g., Haith, 1969; Salapatek & Kessen, 1966). In these methods, direction of regard is calculated from features of the scanning eye recorded with infrared-sensitive movie film or an infrared-sensitive vidicon in a closed circuit television system. A major limitation of the method as it has been applied to infants is that the information on eye position has been obtained off-line by a human scorer. In some cases, the scorers simply view the filmed eye movement record and indicate a judgment of the location in space toward which they think the eye was pointed (Maurer & Salapatek, 1976; Salapatek, 1975, Note 1); the accuracy with which observers are able to make this judgment has not been established. More precise measures of eye position have been derived from digitizing information about the relevant parameters of the eye with graphic or motion analyzers. In these cases, the time required for the hand analysis has been extreme, and experimenters have analyzed only a time-sampled subset of the data at rates of 1-4 Hz across studies. Such studies have not typically been published with information about scorer reliabilities or calibration data on the accuracy of the systems with infants (and sometimes not even with adult observers). There is evidence that there may be developmental differences as well as wide individual variation in the positions of the visual axis for the fovea and the optic axis estimated by using the center of the pupil in eye position calculations (Slater & Findlay, 1972). Correction for such discrepancies requires some dynamic calibration technique, which is not possible with the methods using off-line scoring of eye position. Another problem with such analyses is that, usually, every calculated set of coordinates is simply called a "fixation," although the eye could have actually been in motion when sampled. A good portion of the data is never analyzed, and information about the durations of fixations and eye movements in real-time is not recoverable.

We have developed a system for recording the eye movements and fixations of infants under seminatural viewing conditions in which information about eye position is available automatically at a much faster sampling rate than in previous work with infants. No human judge is required to estimate eye position. Calculation of eye position is on-line, offering the potential for changing the visual display as a function of current eye position. The sampling rate (60 Hz) is rapid enough that records of eye position can be parsed into epochs of fixation and movement of varying duration, rather than being time-locked to the sampling rate. We have also devised calibration procedures for estimating the accuracy of the system with infants and adults (see Harris, Hainline, & Abramov, 1981).

Address reprint requests to the Department of Psychology, Brooklyn College, City University of New York, Brooklyn, New York 11210. The research reported was supported by Grant GB43888 from the National Science Foundation, Grant 12-19 from the National Foundation, and Grant 12220 from the PSC-BHE Faculty Research Awards program of CUNY. I would like to thank Israel Abramov and James Gordon for their technical assistance and advice.

0005-7878/81/010020-05$00.75/0

EYE MOVEMENT RECORDING SYSTEM

The heart of the system is a commercially available infrared video eye movement monitoring system (Applied Science Laboratories, Model 1994), which we have extensively modified for work with infants, and ancillary software for computer-controlled data acquisition and analysis. The essential elements involved in the estimation of eye position are shown schematically in Figure 1. We start with a low light-level invisible infrared source whose light is collimated so that the rays are parallel when they reach the subject's eye after being reflected by an infrared-reflecting visible-transmitting dichroic mirror. A small amount of the light that enters the pupil is reflected by the retina, passes out of the eye through the pupil, and eventually reaches a very sensitive television camera. This camera provides an enlarged image of the eye with a bright pupil. Actually, only part of the incident light enters the eye; a fraction is reflected by the cornea and appears on the television image as a small, bright, virtual image, the corneal reflection or the first Purkinje image, superimposed on the bright pupil. Because the cornea and the rest of the eye have different radii of curvature, as the eye rotates about its center of rotation to look at a portion of the visual field, the corneal reflection moves differentially with respect to the pupil. If, however, the entire head moves, within limits, the pupil and the corneal reflection move together. Thus, if the position of the head is stabilized, analysis of shifts of the corneal reflection relative to the pupil can specify direction of regard (as in the bottom panel in Figure 1).

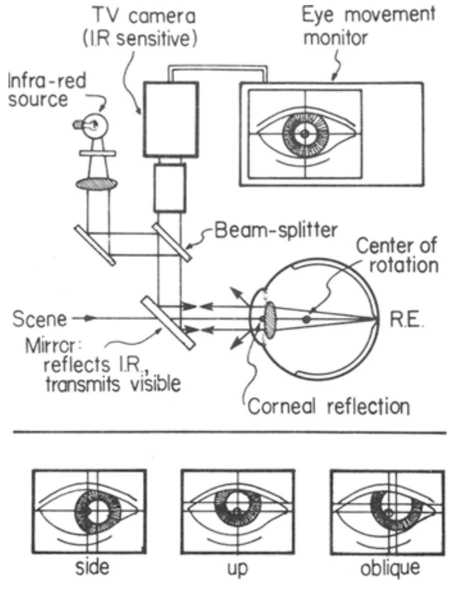

Figure 1. A schematic representation of the essential elements and principle of operation of a television-based infrared eye movement recording system. The lower portion of the figure illustrates the differential movement of the corneal reflection with respect to the pupil during eye movements.

In the ASL Model 1994 eye view monitor, hardware circuitry detects the location of the pupil relative to the brighter corneal reflection in the video image, and it calculates points of regard as sets of X,Y coordinates. The calculated point of regard, in addition to being available as digital information, is also displayed on a television monitor as the intersection of a set of crosshairs superimposed on an image of the scene being viewed. The manufacturers claim a calibrated accuracy of at least ±.5 deg, which we have confirmed in our system in its current configuration with adult subjects. The manufacturer gives a method of calibrating the system for each individual observer; however, their method is not applicable to infants, and we have had to devise a new approach (see Harris et al., 1981). Since the method for calculating the X,Y coordinates of eye position in our system has not been modified from the manufacturer's system, it will not be discussed further.

For the purposes of recording eye movement information from infants, advantages of the ASL system, which is unique among commercially available systems of moderate cost, are that some degree of head movement can be tolerated and nothing is attached to the infant's head. The manufacturer's configuration calls for the camera to be located off the axis of the observer's eye at an angle of approximately 30 deg. We found, possibly because of the smaller size of the infant eye or some characteristics of the infant eyelid, that we often had difficulty in obtaining a good video image of the eye and that infants were also prone to look at the camera lens, regardless of how we masked it. Consequently, we changed the location of the camera to a position equivalent to 50 cm straight ahead of the eye by introducing a large dichroic beam splitter at a 45-deg angle in front of the subject's eye, with the camera at right angles to the eye. The mirror, a 33 x 33 cm Libby Owens Ford mirror with No. 436 coating, reflects 80% of the incident infrared light while transmitting about 80% of the visible light. The mirror is mounted with the near edge approximately 5 cm from the plane of the subject's eye, with mirror mounts that do not obscure any of the visual stimulus (CRT screen, rear-projection screen, or real object) presented 50-80 cm in front of the subject. When the room lights are out, as in an experimental session, the mirror, although directly in front of the subject, is virtually invisible, and the subject looks through it at the stimulus. We find that obtaining a good view of the eye with the camera in this configuration is easier and that the camera lens is not in the visual field to distract the infant.

Another change we found necessary involved the system of filters for the illuminator. It is a common, although erroneous, belief that the human visual system is insensitive to infrared light (750 nm or longer); in fact, depending on its intensity and the viewer's adaptive state, infrared light may be quite visible. With the filters supplied by the manufacturer, the illuminator (a 100-W tungsten bulb) was invisible only if room and stimulus illuminators were at photopic levels. Moving to mesopic or scotopic levels resulted in a rather large and visible red image of the illuminator superimposed on the stimuli. Since we were concerned about maximizing infant attention to the stimulus by running our studies at low ambient light levels and we could not instruct our subjects simply to ignore the residual visible image of the illuminator (toward which they readily looked), we explored alternative filters. We are currently using a set of filters consisting of a Corning 7-69 filter to remove very long wavelengths and a pair of orthogonal crossed Polaroid filters (Type HN-7) (Haith, 1969). These, together with the infrared reflectance of the dichroic mirror, make the illuminator largely invisible; only a dark-adapted observer is able to detect a faint red image when no illumination is provided by the stimulus. As a result of the change in filtering and the introduction of the beam splitter, the amount of light reaching the camera was sometimes insufficient for the pattern-detecting circuitry of the apparatus to operate properly. We therefore changed to a faster lens (a Soligor 135-mm f1.8 lens with a 2X extender and a spacer for close focusing; the effective focal length is 270 mm, with an f ratio of approximately 3.5-4). The resulting narrow band of infrared light reaching the eye has a peak at 970 nm, with a half-power bandwidth of 100 nm. The irradiance at the subject's cornea is less than 4×10^{-4} W/cm^2, well under the suggested safety limit for chronic IR.A irradiance at the cornea, which is 10^{-2}W/cm^2 for adults (Sliney & Freasier, 1973). The peak transmission of the filters matches the characteristics of the silicon vidicon tube in the eye camera fairly well.

USE OF THE SYSTEM WITH INFANTS

Existing infant systems (Aslin, in press; Haith, 1969; Salapatek & Kessen, 1966) record the eye movements of infants who are lying on their backs with their heads on a mattress or in a sling-like holder. The infant is often given a pacifier to suck on to keep the head positioned at the midline. In these systems, the infant is positioned in a small space under the eye movement recording equipment, making the systems difficult to use with older children and adults. Perhaps a more serious drawback of systems in which the infant is lying on a hard surface looking up at the stimulus is that, depending on the size of the infant's head, the eye will be at different distances from the stimulus for different infants; also, if an adult's head is placed in the same position as that of the infant, the adult's eye will be closer to the stimulus, making calibration information obtained from adults of questionable relevance for estimating errors for infants. Also, the unrestricted use of pacifiers during viewing to maintain head position might be questioned, since there are indications that pacifiers, as their name implies, may qualitatively change the nature of infant looking behavior from that observed in nonpacifier conditions (Bruner, 1973).

For these reasons, we designed the superstructure of our apparatus to allow the infant to be held in an upright or semiupright position (Figure 2). We experimented with a variety of infant seats with head restraints (which many infants disliked intensely) and with X-Y movers (which were too cumbersome and slow) to position the infant seat to maintain a view of the eye as the infant moves. Our final solution was to use a human observer as the "infant seat"; he holds the infant over his shoulder, cradling and stabilizing the infant's head with his hand and the side of his head, moving his body and that of the infant to position the infant's eye properly for recording. In doing so, the experimenter refers to two television monitors: One, for fine tuning, shows a greatly enlarged picture of the eye as obtained by the eye camera, and the other, connected to a low light-level camera with a fast wide-angle lens (25 mm, f.85), shows a wide-angle view of the infant's face (see Figure 2). The second monitor has a locating reticule to aid in positioning the infant. The experimenter has his back to the stimuli and thus cannot see what the infant is looking at. The infant looks through an opening in a baffle and through the beam splitter to the visual scene of interest. Our degree of success in obtaining data on eye movements under these conditions is from 40% to 60%, which compares favorably with the success rates typical of infant research in general. The main reasons for losing subjects' data, besides the usual crying and sleeping, are excessive movement and the pupil's being too small (less than 2.5 mm) or too dim to be detected by the circuitry that calculates point of regard.

Adults and older children can easily be studied in the same apparatus by adding a chinrest in front of the viewing porthole. Another advantage of our physical arrangement is that the eye can be accurately repositioned

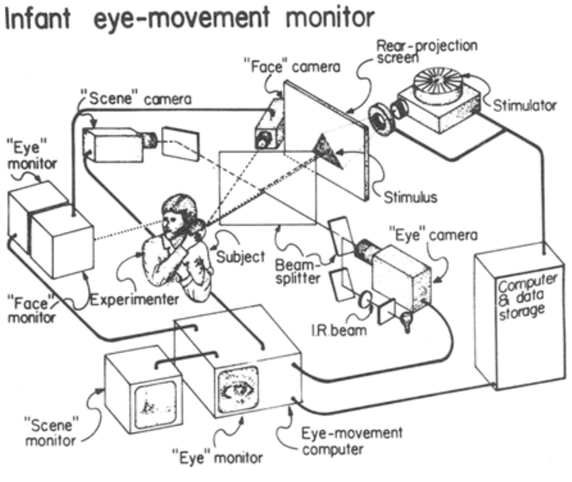

Figure 2. A schematic representation of an eye movement recording system designed for use with infants.

in the same location in space. Permissible head movement parallel to the stimulus screen is limited by the field of view of the camera lens to an area of about 2 x 2 cm. The front-back movement allowed is limited by the depth of field of the lens, which is about 1 cm. In running subjects of any age, we leave the focusing adjustment of the lens at a preset distance, and the subject is moved until his eye is in focus at that constant distance; this insures a constant viewing distance, a factor of particular importance in studies in which the angular subtense of the stimulus is a variable of interest.

DATA ANALYSES

The data in our system are output to a minicomputer (a Digital Equipment Corporation PDP-8/e with 16K of memory), which stores them on magnetic tape in a form readable by a large computer system; the minicomputer also controls all stimulus presentations so that these can later be related to the eye movements. If the eye position information is not used for on-line stimulus control, the system could be simplified to a digital mass storage device for recording the eye movements in computer-compatible form for later, off-line analysis. At present, our data are analyzed off-line. Processing consists of several FORTRAN IV programs designed to reduce the data to a series of fixation and eye movement episodes and to analyze the characteristics of these episodes (i.e., their timing, sequencing, and spatial distribution). Perhaps of greatest general interest is the algorithm for defining a fixation. We use an algorithm that bears some similarity to one described by Mandel (1979). In essence, the method is a pseudovelocity analysis in which the amount of change between successive data samples for X and Y are separately evaluated for both size and direction of change. First, the data are screened for eye blinks

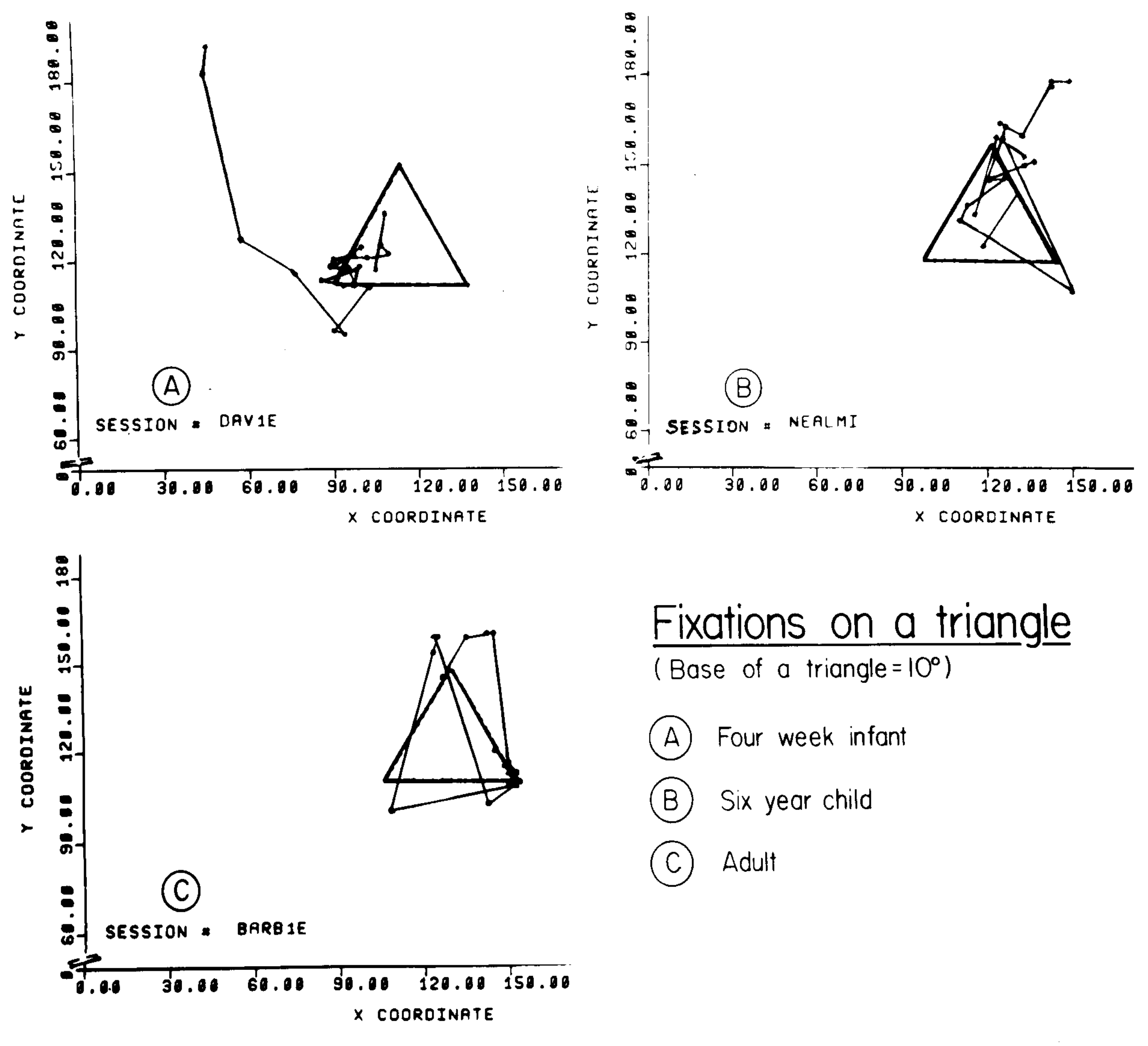

Figure 3. Computer-plotted scanning records obtained from subjects of all three ages viewing a triangle. The data were all collected in the apparatus described; all subjects were at the same viewing distance.

and artifacts that appear in the record as distinctive extreme scores. For the remaining record, the successive difference, or "delta," values represent the distance moved in 1/60 sec (16.7 msec). A fixation is defined by the average of a set of points whose X and Y coordinates show small successive differences with a random sequence of signs for successive differences. If the size of a delta on X or Y falls above some criterion value and stays above this value for a criterion number of samples (in our work, at least three samples, or 50 msec), an eye movement is defined. A movement is also defined if, for X and Y, three successive samples fall below the criterion delta but have the same sign, since this would indicate a slow drift. In our work with both infants and adults, we have found a delta value representing about .5 deg of movement gives reasonable results. The algorithm also has some "smoothing" decision rules to avoid defining sudden and short-lived changes, probably artifactual, as eye movements, thereby artificially breaking a fixation sequence. These reduced records, substantially shorter than the raw data files, are then analyzed for information about the location and duration of fixations and the velocity and duration of eye movements. One typical type of output is a graphic recreation of the scanning pattern shown superimposed on the stimulus; eye movements are represented as lines joining fixation points whose symbols represent different dwell times. Examples of some of these computer-plotted records for individuals of three ages viewing a plane geometric figure are shown in Figure 3.

A final point concerns the accuracy of the system with infants and adults in estimating point of regard in space. With cooperative adults, for whom we can perform the suggested manual calibration, adjusting eye position gain and linearity controls, we are able to achieve the ±.5-deg accuracy in absolute position claimed for the system. If we do no specific calibration for adults (i.e., if the instrument is set for an average observer), we find errors that are highly variable between individuals but range from ±3 deg to the ±.5 deg of the calibrated subject. The estimation of the accuracy of the system with infants involves using a calibration procedure that will work with nonverbal, noninstructable subjects; such a procedure is described in Harris et al. (1981). Based on our analyses of infant calibration data, we find, as with adults, large individual differences in the size and direction of calibration corrections required; the order of the maximum corrections we have observed appears to be ±4 deg, but it is less for many infants. The reasons for these individual differences are as yet unknown, but the general order of magnitude of the corrections allows us to interpret with greater confidence data on scanning obtained from infants from whom we have been unable to collect calibration data.

The system described here allows the rapid and relatively precise recording of eye movements and fixations from infants, older children, and adults in the same apparatus. The data are acquired at a rate that allows the estimation of both the temporal and calibrated spatial characteristics of infant oculomotor behavior, thus permitting a more detailed analysis of infant information processing abilities than has previously been possible.

REFERENCE NOTE

1. Salapatek, P. *The visual investigation of geometric patterns by the 1- and 2-month-old infant.* Paper presented at the meeting of the American Association for the Advancement of Science, Boston, Mass., 1969.

REFERENCES

Aslin, R. N. Development of smooth pursuit in human infants. In D. F. Fisher, R. A. Monty, & J. W. Senders (Eds.), *Eye movements: Cognition and visual perception.* Hillsdale, N.J: Erlbaum, in press.

Bruner, J. S. Pacifier-produced visual buffering in human infants. *Developmental Psychobiology,* 1973, **6**, 45-51.

Haith, M. M. Infrared television recording and measurement of ocular behavior in the human infant. *American Psychologist,* 1969, **24**, 279-282.

Harris, C. M., Hainline, L., & Abramov, I. A method for calibrating an eye-monitoring system for use with infants. *Behavior Research Methods & Instrumentation,* 1981, **13**, 11-17.

Mandel, T. S. Eye movement research on the propositional structure of short texts. *Behavior Research Methods & Instrumentation,* 1979, **11**, 180-187.

Maurer, D., & Salapatek, P. Developmental changes in the scanning of faces by young infants. *Child Development,* 1976, **47**, 523-527.

Salapatek, P. Pattern perception in early infancy. In L. B. Cohen & P. Salapatek (Eds.), *Infant perception: From sensation to cognition* (Vol. 1). New York: Academic Press, 1975.

Salapatek, P., & Kessen, W. Visual scanning of triangles by the human newborn. *Journal of Experimental Child Psychology,* 1966, **3**, 155-167.

Slater, A. M., & Findlay, J. M. The measurement of fixation position in the newborn baby. *Journal of Experimental Child Psychology,* 1972, **14**, 349-364.

Sliney, D. H., & Freasier, B. C. Evaluation of optical radiation hazards. *Applied Optics,* 1973, **12**, 1-24.

Young, L. R., & Sheena, D. Eye movement measurement techniques. *Behavior Research Methods & Instrumentation,* 1975, **7**, 397-429.

(Received for publication June 23, 1980;
revision accepted February 24, 1981.)