INSTRUMENTATION & TECHNIQUES

An eye monitoring system for infant subjects

GORDON W. BRONSON
Mills College, Oakland, California

An eye monitoring system for gathering visual scanning data from infant subjects is described. The video camera that records an image of the eye automatically follows horizontal and vertical head movements, so the infant's head need not be held in a fixed location throughout the course of an experiment. The algorithm used for processing the video records correctly interprets the partially occluded pupils that often are found in very young infants.

The bulk of the visual scanning data on human infants has been acquired with eye monitoring systems of a type developed originally for adult subjects (see Aslin, 1985; Hainline, 1981). The method involves the recording of a video image of a subject's eye, which requires that the pupil of the selected eye be kept within the roughly 2×1.5 cm field of the recording camera. This requirement creates problems for some types of infant research, because infants of more than a few weeks of age often protest when their head movements remain constrained. The limitation is not severe if the necessary data can be collected over a series of brief intervals (as when one is examining the dynamic characteristics of saccades, or the accuracy of visual pursuit; for a review of this kind of research, see Shea, 1992), but it has proved difficult to study how infants scan a visual display across extended intervals of time. The only recent studies that provide data on the characteristics of continuous scanning (Bronson, 1990b, 1991) have been based on techniques that reduced the need for head restraints, but the methods were not fully satisfactory. The present article describes an eye monitoring system designed to overcome this limitation on infant scanning research.

A standard bright-pupil corneal-reflex system remains the method of choice. In this approach, the direction of gaze is determined by measuring the position of the pupil relative to a fixed point on the eyeball, with the fixed reference point being provided by the reflection from the cornea of a small infrared (IR) lamp. With the lamp set coaxially with the camera, light is reflected from the subject's retina, as well as from the cornea, so that the video image of the pupil appears brighter than the surrounding eye and face, thus making the pupil boundary easy to detect. A number of alternative techniques that are sometimes used with adults (see Young & Sheena, 1975) were

considered briefly and rejected: the "dark-pupil" method, in which the pupil boundary is enhanced by using oblique IR illumination, proved ineffective, because during the first weeks of life the iris is a poor reflector of IR light; methods that measure the outer boundary of the iris, rather than that of the pupil, will fail because an infant's eyelid often obscures much of the iris; and an EOG only monitors the rotation of the eye within its socket, so that when the head turns, the direction of gaze becomes indeterminate.

At the outset, two alternative approaches were considered for reducing the need for head constraints: either the recording camera could view an unusually large area of the visual field, or it could continuously follow the subject's head movements. Given the video technology available when the system was developed (1988-1991), the former approach was considered less promising. A very high resolution video sensor would be required in order to maintain measurement accuracies, and sensors of this type carry so much information within each video frame that they largely preclude data extraction at relatively high frame rates (i.e., at 30 or 60 Hz). The resulting slow sampling rate would produce fewer data points per fixation and, hence, less accurate scanning records. Therefore, a system in which the camera views the usual rather limited area but follows the infant's head movements was developed.

System Characteristics

The physical arrangement is illustrated in Figure 1A. The entire system is mounted in the bottom of a small box that also contains the stimulus display and a video-recorder for recording the video record; thus, the entire unit is portable. Figure 1B illustrates the functional organization. To provide a "bright-pupil" image of the subject's eye, an IR light source (a) is reflected off the 30% mirror (b) and the movable tracking mirror (c), thus illuminating the eye; light from the eye is reflected back to the camera (d) through the tracking mirror. With this arrangement, the field of IR illumination and the camera field move to-

Reprint requests should be sent to the author at 3456 Dwight Way, Berkeley, CA 94704.

Figure 1. An eye monitoring system that follows infants' head movements. (a) The physical arrangement. (b) A representation of the optical pathways. (The dashed lines indicate the path of infrared light used to illuminate the subject's eye; the solid lines show the path of the reflected light from eye to camera; the dotted lines show the optical pathway from an infrared LED mounted on the infant's forehead to an x,y position sensor. For details of operation, see the text.)

gether as the tracking mirror follows the subject's head movements. The motion of the tracking mirror is controlled by an x,y position photosensor (e), which receives, via the tracking mirror and fixed mirror (f), an image of an IR LED (g) that is positioned on the infant's forehead (with tape, or attached to an infant cap). When the image on the x,y sensor moves off center horizontally, electronic circuits activate a linear stepper motor (h; see Figure 1A) until the image is recentered on the sensor; the optical paths of the sensor and camera coincide, so this concurrently recenters the eye within the camera image. When the LED image on the sensor moves off center vertically, a stepper (i) rotates both the tracking mirror and the camera until the displacement is corrected (the camera view sweeps in a vertical arc centered at the tracking mirror; rotating the camera along with the tracking mirror keeps the camera image of the eye in an upright orientation; to minimize inertial effects, the camera lens remains stationary). In both types of correction, the stepper speeds are proportional to the displacements on the x,y sensor, so tracking speeds vary with the rate of head movement.

The camera views a nominal 2×1.5 cm area of the eye, and the tracking mirror will follow through head movements of about ± 7 cm horizontally and ± 4 cm vertically; the eye remains in focus over changes in distance of about ± 2 cm. (Note that putting an autofocus lens on the camera would eliminate the latter restriction on head movement—but at a cost. Whenever the subject's distance from the stimulus and camera changed significantly, the point of fixation on the stimulus plane would shift and the size of the recorded image of the pupil would be altered—and, unfortunately, the two effects are additive. Therefore, subject motion in this dimension would have to be measured and recorded continuously on the video record, so that appropriate corrections could be made during subsequent calculation of the subject's locus of fixation from the recorded video images.) The x,y sensor that monitors head location spans a 15×15 cm area on the subject's forehead, so tracking will continue even if the pupil should briefly fall "off camera" during a very rapid head movement. Because the forehead LED emits a cone of light covering a roughly 90° angle, tracking will continue when the head is turned somewhat away from the stimulus. The tracking mirror stops moving, however, whenever the LED image disappears from the x,y sensor—that is, when the infant turns more than some 45° away from the stimulus. A control switch will recenter the tracking mirror for the beginning of a new trial. To correct for minor imprecisions in positioning the LED on an infant's forehead, a joystick that alters electronic biases can shift the "centered" location on the x,y sensor, so by checking the monitor image, the pupil can be centered accurately within the camera field at the start of an experiment.

Design Considerations

In selecting the optical and mechanical parameters for the system, various tradeoffs must be made among desired operating characteristics—and the relative weights that are assigned to these characteristics will depend on the questions to be investigated. Therefore, rather than describe in detail the author's prototype system, it seems preferable to focus on the kinds of issues that arise when one makes such decisions. (Some of the major parameters are noted, however, to provide a general sense of how the system might be configured for work with very young infants. Readers who may wish to discuss these matters in more detail are encouraged to contact the author.)

First, consider the choices to be made in setting various optical parameters. The level of IR illumination must be sufficient to produce an adequately bright pupil in the camera image, yet the luminance level of the IR image that is formed on the subject's retina must remain within safe levels (see the American Conference of Government Industrial Hygienists, *Threshold Limit Values and Biological Exposure Indices for 1990-91*). This consideration argues for using a large-diameter IR light source, so that the total flux is distributed over a large-area image on the retina. In a bright-pupil system, the eye acts as a retroreflector; therefore, in order to collect all of the

light that is reflected back through the pupil, the diameter of the camera lens should be no smaller than that of the IR source. The optimal arrangement is to set equal diameters, in which case the brightness of the pupil image will increase as the square of these diameters. A further consideration, however, indicates that these diameters should not simply be made as large as possible in order to maximize pupil brightness for a given IR intensity.

For the accurate processing of the video images, the boundaries of the pupil must be sharply delineated, so the level of contrast between the pupil and the surrounding iris and face should be maximized. To achieve this, it turns out that the (matched) diameters of the camera lens and the IR light source should in fact be kept as *small* as possible. Light from the iris and face is reflected diffusely (spreads in all directions), whereas that passing back through the pupil is collimated (focused in a narrow beam by the lens of the eye), so any increase in the diameter of the camera lens will have a larger effect on the proportion of reflected light collected from the face and iris than on that collected from the pupil. (In the author's system, the diameter of the camera lens is set at 16 mm, giving an f-ratio of around 5.0.)

As a source of IR light, the author has found that a 15-mW LED (emitting at 890 nm) provides sufficient illumination when it is placed in an elliptical reflector. However, with this arrangement, the pupil must be at least 3 mm in diameter if it is to pass enough light to provide an adequately bright pupil, and so the level of ambient light during an experiment must be limited. In the author's experience, presenting illuminated figures set in a dark surround in a semidark room produced sufficiently large pupils in the infant subjects. If such requirements are not considered acceptable, the IR intensity must be increased to accommodate pupils of a smaller diameter; this can be done by using a filtered incandescent lamp rather than an LED to illuminate the subject's eye.

To make it easy to initially position the infant so that the forehead LED falls within range of the photosensor (see Figure 1), the latter should cover a large area of the forehead. This is achieved with the use of a large sensor (a 19×19 mm unit seems to be the largest available), together with a short focal-length lens; the author uses an aspheric lens with an fl of 50 mm and a diameter of 75 mm.

The stimulus figures (not shown in Figure 1) are mounted in a horizontal plane just above the tracking unit. A "cold mirror" set at an angle of 45° in front of the unit passes the IR light used by the eye monitoring system, while reflecting the visible light from the stimulus to the subject's eye. When a subject is allowed horizontal and vertical head movements, the stimulus figures and the tracking mirror must be set equally distant from the subject's eye, or parallax effects can introduce errors when the direction-of-regard data subsequently are converted into fixations on the stimulus plane (see Bronson, 1983). In the author's system, the optical distance from the subject to the stimulus figure (and the tracking mirror) is set at a nominal 28 cm.

For some research issues, it is important to record the moments of stimulus change accurately. In the author's system, these changes activate microswitches which are then translated into bar codes that appear on the top four lines of each video frame. This information is carried through the video processing stages, so that the final scanning output indicates moments of stimulus change along with the current locus of fixation.

Finally, decisions must be made about the mechanics of the tracking system. The linear actuators of the stepper motors have a lag time of about 10 msec, which is adequate for a quick initiation of tracking-mirror motion. There is, however, a problem in rapidly attaining the *speed* required to follow an unusually fast head movement, and in the author's system there will be instances in which the tracking mirror briefly falls behind and the pupil will be "off camera" for periods of perhaps ¼ sec. If brief intervals of missing data cannot be tolerated—and they are likely to be more frequent in the records obtained from highly active, older infants—one should consider using the recently developed "microstepping" controls for the stepper motors, rather than the "half-step" controls used by the author.

Interpreting the Video Record

After an experiment is completed, the video record is translated into a *scanning pattern* by means of a two-step process. First, a frame grabber digitizes each video frame and passes it to a computer, where brightness differences within the current image are used to identify pixels that correspond to the pupil and the "corneal spot" (the latter being the corneal reflection of the IR light source). A series of algebraic algorithms is used to determine the centers of the pupil and of the spot, and to calculate the x,y coordinate differences between them. The latter indicate the momentary direction of regard. Because an infant's pupil is often partly occluded by the lower eyelid, the algorithm for calculating the pupil center draws only on sets of data points that delineate the two sides and the top of the pupil. (In the author's system, six optimal points are selected from each location; also, an "error index" is derived that reflects their coherence with a superimposed circle, so that frames giving poor-quality data can later be identified. The software was written by Opticomp Consulting of Oakland, CA; either they or the author can provide further details on the software algorithms.)

In a second processing step, these direction-of-regard indices, sampled 30 times per second, are translated into a series of discrete fixations. The x and the y direction-of-regard values from successive sections of the video record are represented in analog form in two columns on the computer screen, and, by visual inspection, the points at which the subject shifted direction of regard are determined. With the computer cursor, these points of change are marked on the computer record; the computer then calculates the *average* x and y direction-of-regard values for each fixation, as well as the fixation duration (the number of frames subsumed). These data, along with the indices that indicate the current experimental stimulus, are

then printed to provide a hard-copy record. When plotted, these x, y points illustrate the infant's scanning pattern during the course of the experiment.

Finally, representations of the stimulus figures must be superimposed on the preceding scanning patterns. To do so, the appropriate *size* for a figure and its proper *location* on the scanning pattern must be determined. Because of individual differences in eye geometries, the appropriate "size" and "location" parameters may differ somewhat from one infant to the next, so the parameters should be determined individually for each infant. The calibration procedure requires about 30 sec of experimental time: Fixation data are collected as a small moving rectangle briefly halts at each end of its horizontal traverse, and since the positions of these end points relative to the experimental stimuli are known, the stimulus figures can be sized and positioned properly on the scanning pattern (the procedure is described in detail in Bronson, 1990a; permitting head translations does not invalidate the calibration parameters acquired for an infant).

Evaluation

To date, some two dozen infants of 6–15 weeks of age have been tested, and the overall system works reasonably well. There is little difficulty in initially positioning an infant within the "capture area" (i.e., where the image of the forehead LED falls within bounds of the x, y sensor); the eye then appears on the video monitor, and head movements begin to be followed. In the author's experience, infants of below some 2 months of age will usually look continuously at the stimulus figures for relatively long periods, and prolonged uninterrupted scanning records are obtained quite routinely. Beyond these early ages, however, problems can arise in some circumstances. Older infants are inclined to seek additional visual targets when the presented stimulus proves to be of little interest, and hence they soon may turn away from the display. The forehead LED then disappears from the x, y sensor and tracking stops. If the trial is continued and the infant turns back to the display, the head may not fall within the "capture area" of the tracking system, in which case several seconds may pass before the person holding the infant can reposition the baby. The problem will not arise in "infant-controlled" experiments, because the trials will end when infants turn away from the stimulus; but with other paradigms, there could be "gaps" in the record if the stimulus is not designed to effectively hold an infant's interest.

The accuracy of the data that are acquired will depend in part on the resolution provided by the video image, and this in turn will depend on the quality of the video components (the camera, videorecorder, and frame grabber in the image processing system), and on the size of the recorded image. With the relatively inexpensive units used in the author's system and a 2×1.5 cm camera field, saccadic shifts in the direction of regard can be measured with an accuracy of about $\pm .5^\circ$ of visual angle. The accuracy with which fixations are *located on the stimulus figure* will depend additionally, and in large degree, on the quality of the calibration data. If only age-typical parameter values are used across all infants, constant errors of as much as 6° – 8° may be introduced into the locus-of-fixation data of some of the subjects (Bronson, 1990a). When individual calibration data are gathered from each infant, however, the overall standard error of measurement can be reduced to around $\pm 1.3^\circ$; that is, the error in locating fixations on the stimulus figures will be within these limits roughly two thirds of the time.

REFERENCES

- AMERICAN CONFERENCE OF GOVERNMENTAL INDUSTRIAL HYGIENISTS (1990). *Threshold limit values and biological exposure indices for 1990-1991*. Cincinnati, OH: Author.
- ASLIN, R. N. (1985). Oculomotor measures of visual development. In G. Gottlieb & N. Krasnegor (Eds.), *Measurement of audition and vision during the first year of life: A methodological overview* (pp. 391-417). Norwood, NJ: Ablex.
- BRONSON, G. W. (1983). Potential sources of error when applying a corneal reflex eye-monitoring technique to infant subjects. *Behavior Research Methods & Instrumentation*, 15, 22-28.
- BRONSON, G. W. (1990a). The accurate calibration of infants' scanning records. *Journal of Experimental Child Psychology*, 49, 79-100.
- BRONSON, G. W. (1990b). Changes in infants' visual scanning across the 2- to 14-week age period. *Journal of Experimental Child Psychology*, 49, 101-125.
- BRONSON, G. W. (1991). Infant differences in rate of visual encoding. *Child Development*, 62, 44-54.
- HAINLINE, L. (1981). An automated eye movement recording system for use with human infants. *Behavioral Research Methods & Instrumentation*, 13, 20-24.
- SHEA, S. L. (1992). Eye movements: Developmental aspects. In E. Chelaluk & K. R. Llewellyn (Eds.), *The role of eye movements in perceptual processes* (pp. 239-303). New York: Elsevier.
- YOUNG, L. R., & SHEENA, D. (1975). Survey of eye movement recording methods. *Behavior Research Methods & Instrumentation*, 7, 397-429.

(Manuscript received May 4, 1992;
revision accepted for publication May 7, 1993.)