INSTRUMENTATION & TECHNIQUES

Measurement of eye orientation of monkeys during visual discrimination¹

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This paper describes apparatus and procedures for measuring eye orientation in the rhesus monkey without restraining the head. The main components of the apparatus are (a) a helmet on which are mounted the discriminative stimuli and the optical and other devices for obtaining a corneal reflection, (b) a special restraining chair that allows the monkey to respond to pushbuttons in front of him, yet prevents him from reaching the equipment mounted on the helmet, and (c) systems for presenting stimuli, monitoring choice responses, and recording eye orientation, which are controlled by a LINC-8 computer. The initial findings on eye orientation during performance on both a hard and an easy brightness discrimination problem are also presented.

A variety of behavioral techniques have been employed (D'Amato & Fazzaro, 1966; Prokasy, 1956; Rees & Schrier, 1967; Wyckoff, 1952) to measure visual observing behavior² of animals on learning tasks, but none have involved systematic measurement of eye movements themselves. In general, little work has been done on eye movements of animals. Fuchs and Robinson (1966) adapted Robinson's method of recording human eye movements for use with macaque monkeys. The method, as used with monkeys, involves embedding a coil of fine wire (the "search" coil) beneath the bulbar conjunctiva and determining the movements of the coil by measuring the current generated in the coil by horizontally and vertically oriented alternating magnetic fields. Fuchs (1967), concerned primarily with monkeys' visual tracking abilities, measured eye movements in response to both discrete and continuous displacements of a spot of light. Head movements were controlled by training the animals to use a bite bar. The monkeys' eye movements were found to be qualitatively similar to those of humans, although uniformly faster. On the average, a 5-deg horizontal saccade took humans 30 msec but took monkeys only 23 msec. The difference increased with the distance of the saccade. A 30-deg human saccade

took almost twice the time of a comparable monkey saccade. Fuchs and Robinson (1966) report the technique to be accurate to $\frac{1}{2}$ deg or better. One possible drawback of the technique is that the operated monkey may suffer from diplopia. Also, there is apparently some tendency for the wires in the animal's head to break. Cowey (1963) developed a method, based on corneal reflection, for measuring eye orientation of monkeys for purposes of conducting perimetric studies of visual-field defects (Cowey & Weiskrantz, 1963). Head movements were limited by training the animals to observe the stimulus display through a mask. Eye orientation was inferred from the location of the center of the pupil with respect to the location of the corneal reflections of four light sources. Although this modification of the corneal reflection method is less sensitive to head movements than those involving a single light source, the necessity of using four corneal reflections makes it very difficult to analyze eye-orientation records automatically.

The purpose of the present paper is to describe another technique for measuring eye orientation in monkeys and to present the initial results on eye orientation during performance of brightness discrimination tasks. The apparatus is a modification of Mackworth's head-mounted "eye-marker" apparatus (Mackworth & Thomas, 1962). The Mackworth technique involves superimposing a corneal reflection on a moving picture or other record of the general scene being viewed by the S. The basic components of Mackworth's system are mounted on a helmet, so that S's head is free to move. These components are (a) a camera objective lens (the scene lens), which forms an image of the visual field, (b) a light source, which produces a corneal reflection, and (c) a second lens (the eye lens), which is focused on the corneal reflection. In one version of the apparatus, the images of the scene and eye spot are transmitted via separate fiber optics cables to an optical mixing box, located off the helmet. Here the two images are superimposed and the combined image transmitted to a TV camera or to a moving-picture camera. In our work with monkeys thus far, the optics have been simplified by eliminating the scene lens. This was accomplished by mounting the

discriminative stimuli on the helmet. With the position of the stimuli (that is, the "scene") thus constant with respect to the head, there was no need to superimpose the images of the scene and the eye spot. Also, we have developed a method of on-line computer recording and analysis of the location of the eye spot.

METHOD

Apparatus

The main components of the apparatus are (a) a helmet on which are mounted the discriminative stimuli and the optical and other devices for obtaining a corneal reflection, (b) a special restraining chair, which allows the monkey to respond to pushbuttons in front of him, yet prevents him from reaching the equipment mounted on the helmet, and (c) systems for presenting stimuli, monitoring choice responses, and recording eye orientation, which are controlled by a LINC-8 computer.

The helmet. The first requirement for successful adaptation of the eye-marker apparatus for use with monkeys was development of a device that would permit us to mount the necessary equipment on the monkey's head, and, furthermore, would hold the equipment in a constant position with respect to the eyes. We devised a helmet for this purpose that is held firmly in place by means of a brace that is placed over the upper teeth. The mouth brace and helmet are removable.

The helmet is made of metal bands, 2.5 cm wide and 2.5 mm thick and lined with 5-mm-thick felt. One of these, the "side" band, extends around the sides and back of the animal's head, closely following its contour, and then extends forward on either side to a point just beyond the front of the mouth (Fig. 1). This band is located just beneath the occipital protuberance, thereby providing one anchoring point for the helmet. The part of the side band just opposite the mouth has slots on both sides that accept bolts embedded in the mouth brace. A "transverse" band passes over the top of the monkey's head and is attached to the side band on the left and right side. The head-mounted equipment is attached to an "equipment" band, which is attached to the midpoint of the transverse band and extends posteriorly just above the midline of the top of the head; the other end is

Fig. 1. Photograph of the helmet and equipment mounted on it. The helmet has been mounted on a plaster cast of the S's head. A = center stimulus-light. B = fiber optics cable. C = mouth brace. D = eye lens. E = side band of helmet. F = light source for the corneal reflection. G = one of the adjustment knobs of the 3-coordinate system.

attached to the posterior part of the side band.

Fabrication of the mouth brace was begun by taking dental impressions of the upper and lower jaws while the animal was under Sernylan (Park-Davis, Detroit, Michigan) anesthesia.³ The mouth brace was fashioned on dental stone casts made

from the impressions. An 18-ga stainless steel reinforcing wire was shaped to the contour of the labial surface of the four upper incisors and then coated with plastic material (autopolymerizing methylmethacrylate and monomer). The process of applying the plastic was repeated until the bar was about 6 mm

thick and shaped exactly to the labial and tooth region. The completed section covered more than one-half of the exposed crown of the teeth and 2-3 mm of the attached gingiva. The heads of two brass bolts, threaded portions pointing laterally, were then attached to the mouth brace on both sides. An 18-ga flat stainless steel band was also attached just anterior to the bolt and crossing the roof of the mouth. The band and bolts were united with the previously formed section using the plastic material noted above. When the mouth brace is applied, the upper incisors fit between the plastic and the metal band, the band preventing the mouth brace from sliding up. The finished mouth brace is very durable and can always be repaired by painting on additional layers of plastic. This material bonds well even to sections that are already cured and hard.

When the mouth brace is in place, the two bolts project out from both sides of the animal's mouth (Fig. 1). The bolts insert in the slots in the anterior portion of the side bands of the helmet and are locked in place by means of wing nuts. The mouth brace elevates the upper lip somewhat, but the animal is able to ingest and chew solid food without apparent difficulty. The mouth brace holds the helmet firmly in place except when the animal jerks its head violently, an occasional occurrence but not a major problem.

Placement of the helmet and the mouth brace on the monkey requires two persons and some care; with practice it takes about 1 or 2 min.

The restraining chair. The major requirements of a restraining chair for our purposes were that the animal be prevented from reaching and displacing the equipment mounted on the helmet, yet be able to see visual stimuli and manipulate devices located on a panel in front of the animal. The hard plastic neckpieces of standard monkey restraining chairs contact and thereby interfere with the positioning of the helmet. Also, downward head movements would cause equipment mounted on the helmet to strike the top plate of the chair which holds the neckpiece.

Fig. 2. Diagram of the top of the restraining chair. Not drawn to scale.

A standard, commercial restraining chair (Lehigh Valley Electronics, Foglesville, Pa.) was therefore modified as follows. The top plate was removed and replaced with a sheet of strong nylon fabric (the nylon cover) with a keyhole-shaped opening cut into it (Fig. 2). The eye of the keyhole is just large enough for the neck of the animal. A nylon cord within the fabric surrounding the keyhole can be tightened and tied behind the animal's neck to secure the animal in the chair. The slit of the keyhole is closed by means of a zipper. The nylon cover is cone-shaped with the neck hole at its apex and fits snugly over the animal's shoulders. An arm slot was cut in the nylon cover sufficiently far forward to permit the animal to reach devices mounted on a response panel facing the animal. The animal's movements are further restricted by a restraining bar located just behind the arm slot and almost in contact with the nylon cover. The bar is attached to the frame of the chair on each side. The slot arrangement, together with the bar, make it impossible for the animal to touch the equipment mounted on the helmet.

The animal is placed in the chair at the beginning of each test session and removed at the end of the test session. The chairing can be done by two persons, but three is best, and takes less than 5 min.

Stimulus-presentation and response-recording systems. The helmet supports (1) a three-coordinate adjustment unit (X-Y-Z compound mechanism), on which is mounted the eye lens, (2) the light source for the corneal reflection,⁴ and (3) three stimulus lights (Fig. 1). The helmet and equipment mounted on it weigh about 2.5 kg and must be counterweighted.

The adjustment unit holds the eye lens opposite the animal's right eye.⁵ Fine adjustment of the position of the eye lens with respect to the eye is achieved by rotating three knobs, one for distance from the eye, a second for horizontal position, and a third for vertical position. The light source for the corneal reflection consists of a lamp (No. 337, General Electric) housed in a small enclosure behind a lens and operated at 6.3 V ac. This light source is mounted at a distance of about 7 cm from the right eye, just to the left of the vertical midline of the animal's face, at about the height of the orbital ridge. Each of the three stimulus-light sources mounted on the helmet consists of a small pilot lamp assembly with a white translucent lens inserted in one end of a tube, 4.5 cm long with an inside diameter of 1 cm. The other end of the tube is open and faces the animal. The size of the opening can be varied by inserting removable brass caps.

The smallest opening is approximately 0.6 mm in diam (No. 76 drill). The stimulus lights are mounted in a triangular configuration about 18.5 cm in front of the animal's left eye. The light at the apex of the triangle is referred to as the center light. The other two lamps supply the discriminative stimuli for the brightness discrimination and are referred to as the side lights. These are about 5 cm above the center light and about 5 cm apart, which corresponds to about 15 deg of visual angle. The pilot lamps are operated at 28 V dc.

The response panel contains the manipulanda, which, during experimental testing, were three pushbuttons (No. 101-S, Switchcraft, Chicago, Ill.), spaced about 2.5 cm apart and called the center and side pushbuttons, respectively. The response panel is mounted on the frame of the restraining chair so that the pushbuttons are in front of the arm slot in the nylon cover of the chair just within reach of the animal. The pushbuttons are approximately 30 cm from the animal's head.

Banana-flavored whole-diet food pellets (CIBA, Inc., Summit, N.J.), weighing 190 mg, are used as reinforcers and are delivered automatically using a pellet dispenser (Model 1548, Lehigh Valley Electronics, Foglesville, Pa.) mounted on the frame of the restraining chair. Although the animal cannot reach its mouth with its hand, it can readily ingest a food pellet by touching it with its tongue and lifting the adhering pellet into its mouth. A pellet receptacle was fashioned from a stainless steel tube, 7 cm long and 1 cm in diam. A small cupshaped extension projecting from one end of the tube catches and holds the pellet. This pellet receptacle is connected to the pellet dispenser by means of a stiff plastic tube ("Impolene," Eastman Kodak, Rochester, N.Y.), which is rigid enough to hold the pellet receptacle near the animal's mouth, but flexible enough to prevent disturbance of the helmet-mounted equipment that might strike it.

A LINC-8 computer (Digital Equipment Corporation, Maynard, Mass.) controls the experimental events and records the instrumental responses and the location of the eye spot. The design of the interface for control of the experiment and recording of the responses is straightforward and need not be described here. However, the design of the interface for recording the position of the eye spot is not routine and is described below. The eye lens is connected by a coherent fiber optics cable, 3 ft long and ¼ in. diam (Bausch & Lomb, Rochester, N.Y.), to a special TV camera (Massey Dickenson

Company, Inc. Saxonville, Mass.). The outputs of this camera include the horizontal and vertical sawtooth signals of the scanning system as well as the usual radio-frequency and video signals. The vertical sawtooth signal (60 Hz) is connected directly to one channel of the LINC-8 analog-to-digital converter. The horizontal sawtooth signal (15 kHz) is connected to the input of a sample-and-hold amplifier (A400, Digital Equipment Corporation, Maynard, Mass.), the output of which is connected to another channel of the LINC-8 analog-to-digital converter. The output of this amplifier depends on the state of a flip-flop in the computer interface; when this flip-flop is off, the sample-and-hold amplifier samples the input; when the flip-flop is on, however, the output is held at the voltage level that was being sampled at the instant the flip-flop was turned on. A video amplifier (Massey Dickenson Company, Inc.) extracts a brightness signal from the composite video output of the TV camera. When this brightness signal exceeds a threshold value (which ordinarily occurs only when the eye is not moving) the flip-flop is turned on.

The computer program is synchronized with the vertical sawtooth signal from the TV camera. When the voltage of this signal indicates that the TV camera is beginning to scan the central portion of the field (about 4 msec after the last flyback), the computer turns off the interface flip-flop and then waits for this flip-flop to indicate the occurrence of an eye spot. If it does indicate this, the computer samples both the horizontal sawtooth signal (which has been held at the output of the sample-and-hold amplifier) and the vertical sawtooth signal. The horizontal and vertical coordinates of the corneal reflection are then recorded for that TV scan. One determination of the position of the eye spot is made for each TV scan. If the interface flip-flop does not indicate an eye spot before the scanning of the center portion of the field is completed (which takes about 8 msec), the eye spot is recorded as absent for that scan. Whether or not an eye spot is recorded, there is an interval of at least 8 msec before the next TV scan during which the computer monitors behavioral events. The location of the eye spot is sampled during testing at the rate of 60 TV scans ("frames") per second, and the records of eye orientation and manual responses from each trial are written onto magnetic tape during the next intertrial interval.

Reliable recording of the eye spot location depends on maintenance of the eye spot above the minimum brightness level during fixations and also on its shape

and size. These, in turn, depend primarily on proper focusing of the eye lens and positioning of the light source as well as the light output of the source itself. Immediate feedback concerning the quality of the eye spot is achieved by displaying the video output of the TV camera on a TV monitor and by having the computer simulate the eye spot on an oscilloscope. Thus E can make a direct comparison of the eye spot at the TV camera and as it is recorded by the computer.

For purposes of recording the location of the eye spot, the TV field, as represented in the computer, is divided into a 16 x 16 recording grid. At the beginning of a session, the light source for the corneal reflection and the eye lens are adjusted so that the eye spot corresponding to a fixation on the center light is of optimal quality and is centered within the grid. This insures that, in turn, fixations of the side lights will also be located within this grid. The computer is then employed to achieve finer calibration and to maintain calibration throughout the session. When obtaining the data described in this report, S alternately fixated on the center light and the left light during the pretrial warning tone (described later). Thus, about 50% of the eye spots during the warning tone were found in the general location of the center light. Further, 10% to 25% of the eye spots during the warning tone were found in a specific cell in that area. The recording grid of the computer was adjusted so that this latter concentration of eye spots coincided with a specific cell that was designated the "calibration cell." If the apparatus subsequently lost calibration, almost no eye spots were recorded in the calibration cell. Therefore, if, during the last 500 msec of the warning tone on any trial, less than 10% of the eye spots fell in the calibration square, the computer provided an auditory warning that recalibration was necessary. The exact procedure for computer-assisted calibration is somewhat different in our current work because changes in training procedure have changed the pretrial scanning strategy. Nevertheless, the general outline of the procedure remains quite similar.

Tests with a single light in varying locations in the visual field have shown that there is a linear relationship between recorded eye orientation and location of the stimulus light over approximately 24 deg of visual angle in the horizontal direction, and a clear monotonic relationship over at least 30 deg of visual angle. We have not investigated the vertical direction as extensively, but the range of linearity appears to be roughly comparable. The calibration procedure described above insured that most of the eye spots

corresponding to the discriminative stimuli were located in the "linear" region of the recording grid. For the data presented here, each cell in this region of the grid represented about 4 deg of visual angle.

Experimental Procedure

Pretraining. The data on eye orientation reported here were obtained during performance of a simultaneous brightness discrimination task by an adult female rhesus monkey (*Macaca mulatta*). The animal had been pretrained over a period of nearly 2 years, largely because the training coincided with the development of the technique. Training of additional animals is proceeding considerably more quickly. The S was first reinforced, on a CRF schedule, for depressing a pigeon key (Model 1348, Lehigh Valley Electronics) located on the response panel. A discrete-trial procedure was then instituted with a light behind the pigeon key serving as the discriminative stimulus. Once the animal responded consistently to the discriminative stimulus, a spatial separation of stimulus and response was introduced. A small pilot lamp (28 V dc) in an assembly with a white translucent lens, mounted just above the key, was used for this purpose. Correct responding at the initial and some of the larger separations was greatly facilitated by use of a fading procedure. With this procedure, both the key and the pilot lamp above it were first illuminated simultaneously; then, over a series of trials, the intensity of the key light was gradually reduced until it was no longer visible.

The animal was then trained on a simultaneous brightness discrimination task using a panel with two pushbuttons, each with a pilot lamp assembly (side light) just above it. One side light was illuminated on each trial, and the animal was reinforced for pressing the pushbutton on the same side. The animal responded consistently and accurately on this problem after one or two sessions. The separation between the pushbuttons and the pilot lamp assemblies was increased in several steps to about 45 cm, using the fading technique when necessary. During the preceding training on the brightness discrimination and during all subsequent training, the helmet was placed on the animal's head at the beginning of testing each day. Only the helmet, held in place by the mouth brace, was used at first, with the helmet-mounted equipment being added gradually. By this time, the animal was eating its complete daily food ration (about 450 pellets) during training.

The helmet-mounted lamps, with their widest opening, were then substituted for the panel lamps using the fading procedure. Once illumination of the panel lamps was eliminated, the size of the opening of the

helmet-mounted lamps was gradually reduced to the smallest size. With practice, the animal was able to reach a near-perfect level of performance on the brightness problem under these conditions, and almost always maintained that level after that. It should be kept in mind that mounting the stimulus lights on the helmet insures that the positions of the discriminative stimuli will remain constant with respect to the head, just as would immobilizing the head.

The third stimulus light and pushbutton (center light and pushbutton) used in experimental testing were added with little difficulty.

Experimental training. The beginning of each trial was signaled by the onset of a 400-Hz tone. After a variable interval selected at random from among four values (1.5, 2.5, 3.5, and 4.5 sec), the center light was illuminated for a maximum of 320 msec, while the tone remained on. If the animal pressed the center pushbutton within 1.6 sec after the onset of the center light, one of the side lights was illuminated (or, depending on the problem, one was illuminated more brightly than the other), and the tone was terminated. The animal was then reinforced for pressing the pushbutton on the same side as the brighter side light, with no correction allowed. If the animal did not respond to one of the side pushbuttons within 4 sec following the response to the center pushbutton, the trial was terminated. If the animal did not respond to the center pushbutton in time, or if it responded to it during the tone but before the onset of the center light, the trial was terminated and the intertrial interval begun. The variable intertrial interval was selected at random from among four values, 4, 6, 8, or 10 sec. Each response during the intertrial interval delayed the next trial for 4 sec. The side that was positive on a given trial was determined randomly, with the restriction that each be positive about equally often each session.

The purpose of the tone and short duration of the center light was to force S to maintain fixation on the locus of the center light during the tone. A sustained fixation has the advantage of making it considerably easier to adjust the size, shape, and brightness of the eye spot and its location for purposes of calibration. The duration of fixations is normally much too short to enable one to judge easily the quality and location of the eye spot, the usual display on the TV monitor being that of a bright spot darting about extremely quickly. As it turned out, S developed a scanning pattern that consisted of a rapid alternation of fixations on the center light and fixations on the left light. These

repeated fixations on the center light during the tone interval served adequately for calibration purposes as described earlier. Nevertheless, a sustained fixation during the tone period is to be preferred, in part because it provides a uniform starting point for fixations on each trial, which simplifies certain aspects of the data analysis. We have recently been able to produce fixations lasting five to six times longer than the average by delaying the onset of the center light if saccadic eye movements occur during the tone period. Monkeys have previously been trained to sustain fixation on a given locus (Fuchs, 1967), sometimes for as long as 20 sec (Scott & Milligan, 1967), but there was only one predictable stimulus locus in these instances.

The data presented in the Results section were obtained during two consecutive blocks of sessions. During the first block ("hard" problem), the brightness discrimination was made more difficult than it had been during the pretraining period by changing the voltage applied to the negative side light from 0 to 20, while the voltage applied to the positive side light remained at 28. During the second block ("easy" problem), the voltage applied to the negative side light was again 0. Both blocks consisted of 13 daily sessions, each lasting about 400 trials. Approximately the first 30 trials of each session were devoted to adjustment of equipment and calibration, so the data from these trials were not used. The results for the hard problem were based on a total of 5,283 trials, and those for the easy problem on a total of 4,648 trials.

Data Analysis

For the purpose of data analysis, a "trial" was defined as the period from the response to the center pushbutton to the response to one of the side pushbuttons. A single fixation was defined as a series of TV frames during which the locus of the eye spot did not move more than one cell in either the horizontal or vertical direction. The mean location during such a series was taken as the location of the fixation.

A number of eye-spot records during the course of a session posed a special problem because they were clearly too short (primarily three frames—50 msec—or less) to be fixations. Of these, the majority lasted one frame. Since they were primarily recorded during saccadic eye movements, they were eliminated in the analysis of data. As for the remaining records of exceptionally short duration, many occurred at the very beginning or end of a trial and seemed to be the result of interruption of the computer recording of an ongoing fixation by a pushbutton

response. Therefore, all fixations that overlapped the choice response at the end of a trial were eliminated from the data on the grounds that they could have occurred only after the choice response was initiated and thus could not have had a bearing on the events of the trial. The same, of course, could not be said of fixations occurring at the time of the response to the center pushbutton so they were eliminated only from the data used to estimate duration of fixation. Apparatus and programming modifications that circumvent this kind of interruption of fixations have now been made.

It has long been recognized (Woodworth & Schlosberg, 1954, p. 497) on the basis of research with humans that it is more accurate to talk about a fixation "region" rather than a fixation "point." On the basis of our early tests, we were able to identify easily the general location of fixations on the stimulus lights. Preliminary analyses further suggested that a liberal definition of the region of fixation of a stimulus light was reasonable for our present purposes and this was the 3 x 3 cell area of the recording grid, in the appropriate general location, that included the maximum number of fixations. Using this definition, on 92% of all trials, at least one fixation on one or the other of the side lights was recorded. On the remaining 8% of the trials (NF trials) no fixation on either side lights was recorded. This does not mean that no such fixation occurred at these loci, but that none was registered by the computer.

For some of the research planned for the future, an increase in resolution will be desirable. There is little question that this can be accomplished in part by a reduction in cell size and in the number of cells included in the fixation region, though we have no firm idea what the limits are. An accuracy of ± 1 deg has been reported (Mackworth, 1967) for the "stand camera" version of the eye-marker apparatus under good viewing conditions.

On about 7% of the TV frames during a trial, no eye spot was detected at all. There are several possible reasons for this, including loss of the corneal reflection during saccadic eye movements, during extreme movements out of the recording field, or during blinking by S. The percentage of frames in which no eye spot was detected was about twice as high on NF trials (15%) as on non-NF trials.

RESULTS AND DISCUSSION

The percentage of correct responses made by S on the hard problem was 71, whereas it was 99 on the easy problem.

Of the many measures of the animal's visual behavior during a trial, we concentrated on three: (1) the duration of

Fig. 3. Proportion of fixations on the side lights having durations up to 300 msec in steps of 16.7 msec (1/60 sec). The curve is based on approximately 4,000 fixations from trials on which a correct response was made. The data from the hard and easy problems have been combined.

fixations, (2) the spatial distribution of fixations, and (3) the temporal distribution of fixations. In all cases, the data were analyzed in terms of problem difficulty (hard vs easy problem), which side light was positive (left vs right positive), and whether the fixations in question were on the left or right side light (left vs right fixations). Trials on which the response was correct were treated separately from those on which the response was incorrect in the case of the hard problem. Error trials were not analyzed in the case of the easy problem because there were so few. Unless otherwise stated, the data refer to correct-response trials.

Data on the duration of fixations for all conditions combined are summarized in Fig. 3, which shows the proportion of fixations on the side lights having durations up to 300 msec in steps of 16.7 msec (1/60 sec). The overall median duration of fixation was 147 msec. There appeared to be no striking effect of any of the variables on duration of fixation. The median durations for the hard and easy problems were 150 and 145 msec, respectively; for left- and right-positive trials, the median durations were 151 and 146 msec; for left and right fixations, the median durations were 160 and 145 msec. There was no relationship between duration of fixation and accuracy on the hard problem, the median duration of fixation on incorrect-response trials being 154 msec, very close to the 147-msec duration on correct-response trials.

Gould and Schaffer (1965) concluded, on the basis of a brief review of the literature on humans scanning various types of displays, that there is no general fixation duration, but that the

HARD PROBLEM

EASY PROBLEM

characteristics of the stimulus seem to determine duration. There has not been much systematic work on this question. The average duration of fixation, when making a series of fixations, has ranged from 157 msec (Arnold & Tinker, 1939) for scanning of single letters to 1,800 msec (Gerathwohl, 1952) for scanning certain types of displays on radar scopes. Average fixation duration for adults during ordinary reading is about 250 msec. Tinker (1958) has concluded that 157 msec is the minimum average duration of fixation for humans making a series of fixations. Thus, the durations found for the monkey in the present study are at the low end of the range reported for humans. The fact that the visual task used in the present study was simpler than those in most of the studies with humans may account for the relatively short average duration of fixation in the monkey. On the other hand, Fuchs's data (1967), showing that saccadic eye movements of stump-tailed monkeys are considerably faster than those of humans,

suggest that duration of fixations could be correspondingly shorter for monkeys.

The spatial distribution of all fixations occurring in the center region of the recording grid during a trial is shown in Fig. 4, separately for the hard and the easy problems. This represents almost all fixations during a trial since over 90% are located in the center region. The upper two concentrations of fixations in each grid, outlined with heavy lines, represent what we have defined as the regions of fixations of the two side lights. Over 50% of all fixations during a trial are located in those two regions.⁶ Systematic variation in the location of these lights has shown that, so long as the distance between them remains at 15 deg of visual angle, the distance between the midpoints of the two regions remains four cells. The locus of fixations on the right light appears to be slightly higher than that on the left light for the hard problem because of a slight misalignment of the two ends of the fiber optics cable when that problem was

Fig. 4. Spatial distribution of fixations during trials on the hard (left panel) and easy (right panel) problems. The percentage of fixations that were located in each cell is shown. The data are from trials on which a correct response was made. The cell clusters representing fixations on the side lights are outlined with heavy lines. The grid region represented in the figure is considerably larger, particularly in the vertical direction, than the region in which the position of the eye spot is linearly related to eye orientation.

presented. Fixations located below those on the stimulus lights may be associated with food acquisition and pushbutton responses, among other things. This could not be determined with precision in the present series of tests because the devices in question were not located on the helmet and, hence, were not in calibration. It is quite evident from Fig. 4 that fixations on the left light occurred with much greater frequency than those on the right, suggesting a strong preference for observing the left stimulus (observing preference).

This observing preference becomes apparent when the temporal pattern of fixations of the side lights during a trial is analyzed. To do this analysis, we determined the number of times fixations on one side light were followed by fixations on the other side light (number of scans), disregarding any fixations that were on neither of the side lights. For example, with L referring to a fixation on the left light and R to a fixation on the right light, the pattern L or R would be zero scans, the pattern LR or RL would be one scan, and the pattern LRL or RLR would be two scans. Nonside-light fixations were rarely interspersed within these patterns, so that the number of fixations is essentially the number of scans plus one. Figure 5 shows the proportion of trials on which there were zero, one, and two scans. The proportion of scans greater than two was virtually zero (cf. Siegel, 1969). For both the hard and easy problems, on the majority of trials on which the left light was positive, fixations were on only one light and, reflecting the animal's observing preference, this was almost invariably the

Fig. 5. Scanning patterns for trials on which the response was correct. The figure shows the proportion of trials on which there were zero, one, and two scans. The left panel represents trials on which the left light was positive (brighter) and the right panel represents trials on which the right light was positive. The data for the hard and easy problems are shown separately.

left light (97% of the trials). Occasionally, fixations on the left light were followed by fixations on the right light during left-positive trials (one scan), but rarely did the animal make two or more scans. On the other hand, appropriately, when the right side light was positive, on the majority of trials S made one scan, which again means that fixations on the left light were followed by fixations on the right light. On a relatively large percentage of the trials on which the right light was positive, fixations were on only one light, but here again that one was the left on most trials (86%). This was somewhat surprising in the case of the easy problem because accuracy was unimpaired.

One possible explanation of this last outcome has to do with the fact that the animal can respond correctly consistently while observing only the light on one side by following the conditional strategy: If the one side light is on immediately after the response to the center button, press the button on the same side; if the one side light is off immediately after the response to the center button, press the button on the opposite side. We tested for this by interspersing among the regular trials of one session, trials on which the onset of the tone and center light was not followed by onset of either of the side lights. On 19 of 20 such trials, the animal responded to the left side, strongly suggesting that the strategy just outlined was not the one S was using. Another possibility, especially because a simple brightness discrimination was involved, is that S was relying on peripheral vision on the trials in question. If that is the case, frequency of fixations on the right side should increase when S is presented form discriminations and others which are less likely to be solved on the basis of peripheral vision. A decrease in the brightness difference between the positive

and negative stimuli might also be expected to increase these fixations in the case of a brightness discrimination. An analysis of the difference in scanning patterns on the hard and easy problems suggests that this occurred to some extent in the present situation. The percentage of trials on which S made one or more scans was 35 on the easy problem and 50 on the hard, so, as might be expected, S did more scanning on the hard problem. The major effect of the hard problem was to decrease the relative frequency of zero-scan trials and increase the relative frequency of one-scan trials. Considering that S's first fixation on a trial is on the left light, this means that S tended to fixate on the right light more frequently when the problem was the hard one.

Is S's scanning behavior the same on correct and incorrect trials? Figure 6 shows the scanning data for incorrect trials on the hard problem together with the data for correct trials on the hard problem that were presented in Fig. 5. Because the order in which S observed the stimuli was the same for correct and incorrect trials, these data strongly suggest that S's scanning behavior on incorrect trials was what would have been appropriate if the negative stimulus had been the positive. For example, on left-positive trials, S fixated on the right, or incorrect, light more frequently when responding incorrectly than when responding correctly; similarly, on right-positive trials, S fixated on the left, or incorrect, light alone more frequently when the response was incorrect than when it was correct. The accuracy of the instrumental response was clearly related to the scanning pattern on a given trial. When the left light was positive, the instrumental choice response was correct on 88% of the trials if S only fixated on the left light; however, accuracy

Fig. 6. Scanning patterns on the hard problem with the data for trials on which the response was correct and incorrect shown separately. The figure shows the proportion of trials on which there were zero, one, and two scans. The left panel represents trials on which the left light was positive (brighter) and the right panel represents trials on which the right light was positive.

dropped to 55% if S made one or more scans. When the right light was positive, on the other hand, the instrumental choice response was correct on only 50% of the trials if S fixated on the left light exclusively, but on 80% of the trials if S made one or more scans.

Another indication of the temporal distribution of fixations is the median latency of the end of the last fixation on either side light (specifically, the time from the response to the center pushbutton to the end of the last complete fixation on either of the side lights). Figure 7 shows this latency in relation to the number of scans. Also shown is the median latency of the instrumental choice response. Both latencies increase as the number of scans increases. The relationship between the

Fig. 7. Median latency of the instrumental choice response and of the end of the last complete fixation on either side light in relation to the number of scans. The starting point in both cases is the response to the center pushbutton. The data are from trials on which a correct response was made and have been combined for the hard and easy problems. The medians are based on 4,786, 2,484, and 178 trials for zero, one, and two scans, respectively.

latency of the end of the last fixation and the number of scans seems quite simple: Latency increases by approximately 150 msec, the average duration of a fixation, with each additional scan. There is some tendency for the interval from the end of the last fixation to the choice response to decrease as the number of scans increases; it was 239, 158, and 150 msec for zero, one, and two scans, respectively. Assuming that the speed of response is constant, this finding would imply that the instrumental choice response was initiated earlier relative to the end of the last fixation, when one or more scans occurred.

Overall median choice response latency was 421 msec. It varied little with problem difficulty (430 msec for the hard problem and 408 msec for the easy) and with the side that was positive (431 msec for right-positive trials and 408 msec for left-positive trials). Overall median latency of the end of the last fixation on either side light was 197 msec. As the results on scanning patterns suggest, latency of the end of the last fixation was greater for right-positive trials than for left (224 msec vs 169 msec) and greater for the hard problem than for the easy (215 msec vs 184 msec).

We cannot claim that the present results are final or definitive. They are based on tests of a single animal who had exceptionally long training. It is possible that some of the eye-orientation patterns described were inadvertently reinforced during the long development period, so we plan to test additional animals before moving on to other problems. Nevertheless, it seems clear that the technique described in this report can yield useful information about eye orientation during performance on discrimination tasks. It can also provide general information about the characteristics of eye movements of monkeys, about which relatively little is known.

Studies of orienting behavior during discrimination learning have importance in their own right, but interest in them has increased in recent years as a result of the two-stage or attentional theories of discrimination learning (Lovejoy, 1968; Mackintosh, 1965a; Zeaman & House, 1963). It has been suggested (Mackintosh, 1965a; Trabasso & Bower, 1968) that overt observing behavior, such as eye orientation, is unlikely to tell us much about the process of selective attention. This is hardly a settled question. For one thing, some of the relevant experiments may have involved tasks or procedures that conceal the role of eye orientation. Also, visual orienting behavior has been studied in only the grossest way in the relevant situations,

so it still seems quite possible that aspects of eye orientation or the pattern of eye orientation will reflect what is being attended to. In fact, a recent discrimination learning experiment with monkeys by Stollnitz (1969), the design of which was an extension of one used in an experiment with rats by Mackintosh (1965b), produced evidence contradicting Mackintosh's conclusion (1965a, b) that observing behavior could not account for the results.

The solutions to some of these problems may depend on our ability to determine the location and pattern of fixations within single stimulus displays. We hope to accomplish something like this in subsequent stages of our work by the simultaneous recording of head and eye movements. This will permit mounting of the stimulus displays off the helmet. It will then be possible to use larger displays and to have greater flexibility in the type of display.

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NOTES

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2. By this term we mean any behavior that results in exposure of a visual discriminative stimulus. The definition is essentially Wyckoff's (1952) as modified by Stollnitz (1965). In recent years, based in part on a misunderstanding of Wyckoff's definition, the term has frequently been used as strictly equivalent to overt, or orienting, behavior. In order to avoid confusion, it would seem best to use the term "orienting behavior" when referring strictly to overt behavior, or else to refer to "overt" observing behavior specifically.
3. We are grateful to Dr. Milton Hodosh of the Institute for Life Sciences, Brown University, for assistance in fabricating this mouth brace.
4. The 3-coordinate unit, lens, and light source were obtained from Polymetric Company, Hoboken, N.J., which produces the head-mounted and other versions of the Mackworth Eye Marker apparatus for humans. Mr. Erwin Streisinger, the manager of this firm, gave us helpful advice about the technique.
5. Unless otherwise stated, we will always refer to the animal's left and right in this paper.
6. With the somewhat more precise calibration that can be achieved with a sustained fixation during the pretrial tone period, as well as some apparatus modifications (notably, a more uniform surround for the discriminative stimuli), we have found considerably less scatter to fixations in the region of the side lights; in this case, practically all fixations in that region are concentrated in two 2 x 2 cell areas.