Saccadic localization of visual targets by the very young human infant

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The direction, latency, and form of the 1- and 2-month-old human infant's saccadic eye movements toward peripheral targets were investigated. Infants of both ages reliably executed a directionally appropriate first saccade toward a peripheral target introduced as far as 30 deg from the line of sight along the horizontal and both diagonal axes, but only to 10 deg along the vertical axis. The presence of a second target in the central visual field reduced the probability of peripheral target localization. A significant inverse relation was found between target distance from the line of sight and probability of initiating a directionally appropriate saccade. Electro-oculography revealed that latency to first saccade, although highly variable, was less than 500 msec on a significant proportion of trials. Unlike the adult, the first saccade to target was grossly hypometric and was followed by one or more saccades of approximately equal amplitude to the first.

Efficient foveation requires a highly sophisticated spatial localization system capable of rapidly translating the line of sight to predetermined peripheral locations. In the human adult, saccadic eye movements toward a peripheral stimulus are of very high velocity (up to 800 deg/sec, see Alpern, 1971, p. 376), have latencies as brief as 120 to 350 msec dependent upon stimulus conditions (Bartz, 1962; Komoda, Festinger, Phillips, Duckman, & Young, 1973; Leushina, 1965; Saslow, 1967; Wheelless, Boynton, & Cohen, 1966; White, Eason & Bartlett, 1962), are highly accurate (Bartz, 1967; Becker & Fuchs, 1969; Rashbass, 1961; Weber & Daroff, 1971), and are ballistic in nature (Westheimer, 1954). The preprogramming of saccadic movements requires the accurate specification of target locus from the current line of sight and the translation of this information into motor commands resulting in a direction- and distance-appropriate eye movement.

In spite of the vast amount of research on the oculomotor system in animals and human adults (e.g., Bach-Y-Rita & Collins, 1971; Davson, 1972; Dichgans & Bizzi, 1972; Grunin & Mostofsky, 1968), few attempts have been made to investigate in detail the saccadic system of the human infant. Although it appears that the young human infant executes saccades during alert viewing of stationary figures (Kesson, Salapatek, & Haith, 1972; Salapatek, 1968;

Salapatek & Kessen, 1966; see Bond, 1972, and Kessen, Haith, & Salapatek, 1970, for general reviews), an exact description of these movements has not been reported.¹ In particular, there has been no detailed investigation of the latency, accuracy, and form of infant eye movements toward a single, small peripheral target introduced into an otherwise patternless field.

Tronick and Clanton (1971) investigated eye-head coordination in 4- to 15-week-old infants. However, they provided only a qualitative description of various eye- and head-movement patterns. Their use of multiple targets in the visual array precluded detailed description of (a) directionality of the first eye movement to a peripheral target, (b) amplitudes of localizing saccades, and (c) latency to initiate an eye movement to a peripheral target. Tronick (1972) investigated the time taken by 2- to 10-week-old infants to fixate a single peripherally introduced target, but did not report the form of the eye movements executed during localization. Moreover, a fixated central stimulus remained on after the introduction of the peripheral target. He found that infants took an average of approximately 3 to 5 sec to localize the target. This long average latency may have resulted from the attentional "capture" of the infant's gaze by the central fixation stimulus, which has been reported by several infant investigators (Ames & Silfen, Note 1; Mundy-Castle & Anglin, Note 2; Salapatek, Note 3; Stechler & Latz, 1966). In a more recent study, Harris and MacFarland (1974) showed that even newborn infants would shift their gaze towards the side of the visual field in which a peripheral target was introduced. Moreover, targets were localized at a greater distance if a central stimulus which the subjects were initially fixating disappeared at the time of peripheral target onset

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than if the central stimulus remained on. Although this study strongly suggests some directional specificity in the saccadic system at birth, the nature of their recording of localizing saccades (human observers) precludes any statements regarding the latency, amplitude, or form of a localizing saccade.

At birth, the localization of a peripheral target may be accomplished as in the adult. That is, retinal local signs for target direction and angular distance may result in highly accurate and ballistic first saccades. Alternatively, there may be neither local signs nor effective motor mechanisms to insure direction- and distance-appropriate localizing saccades. Although the Harris and MacFarlane study indicates some directional specification at birth, the development of accurate saccadic localization might proceed by a learning and/or maturation process involving either the receptive or the motoric systems, or both. For example, McLaughlin (1967) has shown that adults are capable of rapidly recalibrating the distance component of the saccadic system, but there are no human infant data indicating either that initial appropriate distance calibration exists or that rapid recalibration of this component is possible. From anatomical evidence, it would appear that the saccadic system must undergo *some* developmental calibration due to (a) shifts in retinal cell loci relative to the optic axis (Mann, 1964), (b) large increases in eyeball mass (Todd, Beecher, Williams, & Todd, 1940), and (c) increases in eyeball diameter which may be accompanied by differential alteration in the dimensions of the various refractive surfaces of the eye (Wilmer & Scammon, 1950). These changes make it very unlikely that either retinal local signs or a fixed motor program specifying target distance and direction remain invariant during development.

This study describes the probability, latency, direction, and form of the infant's eye movements toward a peripheral target replacing or added to a central fixation stimulus. To assess these parameters accurately, electro-oculography (EOG) as well as direct observation, was employed.

METHOD

Subjects

Twenty-four 1-month-old human infants (12 males and 12 females; mean age = 32.5 days, range = 25-37 days) and 24 2-month-olds (15 males and 9 females; mean age = 61.0 days, range = 55-67 days) were sequentially assigned to one of four experimental groups. All subjects were Caucasian, home reared, above 2,750 g at birth, and obtained on a volunteer basis by phone solicitation based on newspaper birth announcements. An additional 16 subjects were eliminated from the study as follows: 11 1-month-olds (1 sleepy, 9 inattentive to a central fixation stimulus, and 1 because of poor observer agreement) and 5 2-month-olds (1 sleepy and 4 inattentive to a central fixation stimulus).

Apparatus and Stimuli

Supine subjects viewed the stimuli by looking at a rear-projection

screen reflected into a half-silvered mirror (see Figure 1). The mirror was fixed at 45 deg with respect to the projection screen. The viewing distance from the center of the stimulus field to the subject was approximately 35 cm.

The apparatus was designed to display small annular targets in the center and at various peripheral locations on a dark gray background (average luminance = 2 fL). Target diameter was 26 mm (approximately 4 deg at field center), annular width 3 mm, and annular luminance 10 fL. One Kodak Carousel projector was used to project a target in the center of the stimulus field. A second projector presented targets at any of the 24 locations peripheral to the center of the stimulus field.

Each trial consisted of the presentation of a target in the center of the stimulus field (central fixation stimulus) followed either by (a) the addition of a target in the peripheral stimulus field (*addition*), or (b) the offset of the central fixation stimulus coincident with the onset of a peripheral target (*replacement*). Each projector was equipped with an Ilex No. 4 Synchro electronic shutter so that durations of target onset and offset were nearly instantaneous (approximately 8 and 5 msec, respectively). In the *replacement* condition, no perceptible delay between central fixation stimulus offset and peripheral target onset, and no motion or afterimage effects were experienced by adult observers.

EOG recordings were attempted on all subjects except those receiving stimuli only along the vertical axis of the stimulus field. Pilot work had suggested that electrode placement below the eye for vertical recording was distracting to the infant. Two Beckman miniature biopotential electrodes were attached to the outer canthus of each orbit using Hewlett-Packard Redux electrode paste and miniature adhesive collars. The skin was rubbed with Beck-Lee Microhm jelly and rinsed with distilled water prior to electrode attachment. A third ground electrode was attached to the midforehead in an identical manner. EOG was recorded ac (time constant = 0.6 sec) on a Gilson Model ICT-1H single-channel polygraph. Sensitivity was kept at 500 μ V/cm and paper speed at 25 mm/sec, enabling EOG potentials to be scored to the nearest 25 μ V and latencies to the nearest 40 msec. With this sensitivity, adult eye movements of 2 deg or more could be detected on the EOG record.

Design

Addition and *replacement* trials were delivered along four axes in the stimulus field. Independent groups of 12 subjects (6 at each age) were presented with *addition* and *replacement* trials along the horizontal, the vertical, or one of the two diagonal axes. Peripheral

Figure 1. Infant eye movement recording apparatus illustrating the positioning of the two observers behind the half-silvered mirror.

targets along the left and right vectors of the horizontal axis were presented at 10, 20, 30, and 40 deg to the left and right, respectively, of the central fixation stimulus; along the vertical vectors at 10 and 20 deg above and below the central fixation stimulus; and along the diagonal vectors at 10, 20, and 30 deg diagonally from the central fixation stimulus.

All subjects also received two types of *control* trials consisting of either (a) the replacement of the central fixation stimulus by a homogeneous gray field (*center-off*), or (b) the addition of a homogeneous gray field to the central fixation stimulus (*center-on*). In each case, the brightness of the resultant gray background was equal to the brightness of the gray background of a peripheral target trial.

All subjects were required to complete at least two blocks of trials. A block consisted of: one *addition* trial and one *replacement* trial at each distance along each vector of a given axis, plus two *center-on* and two *center-off* control trials. Order of trials was random except that each half-block never contained two trials at the same distance along a given vector.

Two observers were stationed behind the mirror, one on either side of the subject (see Figure 1). A shield on the upper rear portion of the mirror allowed the observers to see the subject's eyes through the lower portion of the half-silvered mirror, but not the targets projected on the screen. The two independent observers simultaneously recorded the direction of gaze of the subject by pressing buttons connected to an event recorder. In addition, one observer attempted to keep the subject's head centered during the experiment, usually with the aid of a honey-coated pacifier. The other observer controlled trial onset.

Each stimulus trial began with the presentation of the central fixation stimulus. When the observer controlling trial onset judged that the subject was staring directly up at the mirror (and presumably at the central fixation stimulus), an *addition*, a *replacement*, or a *control* trial was introduced. Trial duration was 10 sec, with a 3-sec intertrial interval, followed by the reintroduction of the central fixation stimulus.

The observers knew each subject's axis, the time of trial onset, and that the subject was looking at the central fixation stimulus prior to trial onset. However, the observers were blind as to the direction and distance of the peripheral target from the central fixation stimulus, and the particular condition (*addition*, *replacement*, *control*) delivered on any given trial. The observers were required only to record, during each 10-sec trial, whether the subject was viewing the center or one of the two semifields defined by each subject's particular axis, e.g., whether the subject was looking up, down, or center, if his peripheral targets were delivered along the vertical axis, etc.

RESULTS

The 1- and 2-month-olds received a total of 916 and 1,036 trials, respectively; more of the 2-month-olds continued past the two-block minimum. Scorer agreement on the direction of first eye movement was 84% and did not differ significantly by age, target distance, condition, or axis. All trials on which there was scorer disagreement were eliminated from further analyses.

Direction of First Eye Movement

A probability ratio for directionally appropriate first eye movements was computed for each subject for each peripheral target along his axis. This ratio was the number of trials on which he made a directionally appropriate first eye movement divided by the total number of trials on which that target was delivered. A

Figure 2. Mean probabilities of making a directionally appropriate first eye movement to peripheral targets, as a function of target distance, for the four axis groups. C = control trial means. Filled circles = replacement trials; open circles = addition trials. RU = right-up vector; LD = left-down vector; LU = left-up vector; RD = right-down vector.

control trial ratio for *center-on* and for *center-off* trials was also computed separately for each subject. These ratios consisted of the number of first eye movements along a particular vector divided by the total number of each type of control trials delivered. Thus, for both *center-on* and *center-off* trials, there existed for each subject a control trial ratio indicating the proportion of trials on which he executed a first eye movement along a particular vector by chance.

Figure 2 presents the mean probabilities of a directionally appropriate first eye movement as a function of peripheral target distance from the central fixation stimulus for *addition*, *replacement*, and *control* trials. Although *replacement* trial means were consistently higher than *addition* trial means across all axes and distances, it should be noted that *center-off* and *center-on* means (control baselines) appear to differ by a similar amount.² A strong distance effect was also indicated for both *addition* and *replacement* trials.

To test these trends, four analyses of variance, one on each axis group of 12 subjects, were computed. Appropriate control trial ratios were subtracted from experimental trial ratios for each subject to eliminate the probability of chance responding. No consistent effects of age, vector, or addition-replacement³ were found. In all four analyses, however, there was a significant main effect for distance (horizontal, $p < .0005$; diagonal RU-LD, $p < .005$; diagonal LU-RD, $p < .001$; vertical, $p < .01$). As Figure 2 indicates, the subjects responded more reliably to near than to far targets. Dunnett's t statistic ($\alpha < .025$) indicated higher experimental than control eye-movement probability at 10, 20, and 30 deg along the horizontal and both diagonal axes, but only at 10 deg along the vertical axis.

Figure 3. Frequency histogram of EOG latencies, in 500-msec intervals, to initiate a directionally appropriate first eye movement on replacement trials for 1- and 2-month-olds. N = number of trials.

Latency of First Eye Movement

EOG recordings were attempted on the 36 horizontal- and diagonal-axis subjects. Sixteen 2-month-olds and 14 1-month-olds provided useful data. From these 30 subjects, a total of 827 scorable EOG trials were obtained, i.e., trials on which both observers agreed upon the direction of the first eye movement and which yielded a scorable EOG record. The EOG record for each trial was scored for direction, latency, and amplitude of the first EOG potential. Slopes of EOG potentials scored indicated that all eye movements here reported were saccadic (see Figure 5). To eliminate poor EOG recordings and to deal with individual variability in the strength of the EOG potential, trials involving targets at 10 deg were scored first for each subject, with knowledge of the observers' combined judgments of first eye-movement direction. This provided, for each subject, an indication of the amplitude of his EOG potential for a 10-deg excursion, which facilitated scoring of his 20-, 30-, and 40-deg trials. Twelve percent of the 249 10-deg trials were eliminated because of disagreement on direction of first movement between the EOG record and the observers' combined judgments.⁴

Each subject's 20-, 30-, and 40-deg trials were scored blind with respect to stimulus condition and observers' judgments, except that the scorer had available the amplitude of each subject's EOG potentials for all 10-deg trials. Approximately 21% of the 578 20-, 30-, and 40-deg trials were eliminated because of disagreement between EOG scoring and the observers' judgments of direction of first movement. This error rate did not significantly vary by stimulus condition beyond 10 deg but was slightly higher than on 10-deg trials, since the EOG scorer could not appeal to observers' judgments in cases where the EOG record was ambiguous.

Figures 3 and 4 illustrate percentage histograms of latencies, in 500-msec intervals, to initiate a directionally appropriate first saccade across the 10-sec trial duration. On replacement trials (Figure 3), an appropriate first eye movement was generally initiated within 2 sec following offset of the central fixation stimulus at all target distances.⁵ One-month-olds executed first saccades with median latencies of 800, 1,320, and 1,480 msec to targets at 10, 20, and 30 deg, respectively. Medians tests revealed that latencies on 10-deg trials were significantly shorter than on 20-deg trials ($\chi^2 = 10.5$, $df = 1$, $p < .01$), or on 30-deg trials ($\chi^2 = 16.6$, $df = 1$, $p < .001$), or on control trials ($\chi^2 = 18.9$, $df = 1$, $p < .001$). There were no significant latency differences between 20-deg, 30-deg, or control trials.

Two-month-olds executed first saccades with median latencies of 480, 920, and 1,280 msec on 10-, 20-, and 30-deg trials, respectively. Medians tests revealed that latencies on 10-deg trials were significantly shorter than on 20-deg trials ($\chi^2 = 3.85$, $df = 1$, $p < .05$), or on 30-deg trials ($\chi^2 = 28.9$, $df = 1$, $p < .001$), or on control trials ($\chi^2 = 17.0$, $df = 1$, $p < .001$). Latencies on 20-deg trials were shorter than on control trials ($\chi^2 = 9.13$, $df = 1$, $p < .01$), but 30-deg and control trial latencies did not differ significantly. Two-month-olds exhibited significantly shorter latencies than 1-month-olds on 10-deg trials ($\chi^2 = 5.3$, $df = 1$, $p < .05$) and on 20-deg trials ($\chi^2 = 4.27$, $df = 1$, $p < .05$), but no age difference was found on 30-deg trials.

Inspection of latencies on 10-deg trials in the replacement condition suggested the occurrence of a considerable number of saccades with latencies less than 500 msec. The frequency of initiating a saccade within 500 msec following the onset of a 10-deg trial was significantly higher than on control trials at both 1 ($\chi^2 = 4.57$, $df = 1$, $p < .05$) and 2 ($\chi^2 = 29.44$, $df = 1$, $p < .001$) months of age. A similar effect was

Figure 4. Frequency histogram of EOG latencies, in 500-msec intervals, to initiate a directionally appropriate first eye movement on addition trials for 1- and 2-month-olds. N = number of trials.

true for 2-month-olds ($\chi^2 = 4.89$, $df = 1$, $p < .05$), but not for 1-month-olds, on 20-deg trials.

On *addition* trials, the subjects initiated directionally appropriate first saccades only infrequently on all but 10-deg trials (Figure 4). As on *replacement* trials, an appropriate first saccade was generally initiated within 2 sec following the onset of a 10-deg trial, and very often within 500 msec, especially for 2-month-olds. A medians test revealed that 2-month-olds showed shorter latencies than 1-month-olds on 10-deg trials ($\chi^2 = 4.19$, $df = 1$, $p < .05$). Directionally appropriate first eye movements on 20-deg, 30-deg, and *control* trials for the *addition* condition were too infrequent to allow us to draw any firm conclusions regarding latency distributions.

The Form of Localizing Saccades

Infants showed considerable variation in the form

Figure 5. Examples of infant EOG records: (a) a single saccade to a target at 10 deg, (b) a double saccade to a target at 20 deg, (c) a triple saccade to a target at 30 deg, (d) a quadruple saccade to a target at 40 deg, (e) a double saccade to a target at 30 deg followed by a return movement; and (f) an adult record of a single saccade to a target at 30 deg. Time marks represent seconds after target onset.

of directionally appropriate saccades initiated toward peripheral targets. These saccades could be (a) single, presumably normometric,⁶ with no detectable corrective movement (Figure 5a), (b) hypometric, with one or more subsequent saccades in the same direction (Figures 5b, 5c, and 5d), or (c) hypermetric, followed by a return movement (Figure 5e). Single and hypometric saccades were by far the most typical movements; hypermetric saccades occurred on only 19% and 14% of scorable EOG trials for the 1- and 2-month-olds, respectively.⁷

Relative Frequency of Single vs. Multiple Saccades.

A single localizing saccade was defined as a directionally appropriate first saccade with no detectable subsequent movements occurring within 2 sec following saccade initiation. A hypometric saccade was defined as a directionally appropriate first saccade followed by one or more additional saccades in the target direction, each occurring within 2 sec of the previous movement. It seemed reasonable to assume that saccades spaced within 2 sec of one another were probably part of the same attempt at localization. As we shall see, data related to the summed polarity of eye-movement potentials in a localizing series made this a tenable assumption.

It appeared that the subjects would often localize the target by means of a series of hypometric saccades, all directionally appropriate. For example, Figure 5b shows a double saccade to a target 20 deg from field center, Figure 5c a triple saccade on a 30-deg trial, and Figure 5d a quadruple saccade on a 40-deg trial. In order to compare the relative incidence of single vs. multiple saccadic localizations, the number of each type of localizing saccade (single, double, triple, etc.) for each subject was expressed as a proportion of the total number of trials on which he made a directionally appropriate first saccade at each target distance. Proportions thus obtained for each type of localizing saccade were averaged to provide a group estimate of relative incidence. It may be seen in Figure 6 that for targets at 10 deg most localizations

Figure 6. Mean proportions of single and multiple saccades as a function of target distance for 1- and 2-month-olds.

Figure 7. Mean EOG amplitude of all single and multiple saccades per trial (total eye rotation) for each target distance expressed as the percent increase over the mean EOG amplitude on 10-deg trials.

consisted of a single or double saccade. Beyond 10 deg, it appeared that the relative incidence of single saccades decreased and multiple saccades increased, although frequency distributions for targets at 40 deg may have been unstable because of the limited number of observations. Finally, no obvious differences were apparent between 1- and 2-month-olds.

As indicated in Figure 6, for 1-month-olds 57% of 10-deg localizations were single saccades while 43% were multiple saccades. For targets at 20, 30, and 40 deg, single saccades occurred on only a mean of 14% of all trials, while multiple saccades occurred on 86% of all trials. Similarly, for 2-month-olds, 49% of 10-deg localizations were single saccades and 51% were multiple saccades, while for targets at 20, 30, and 40 deg combined, a mean of 24% were single saccades and 76% were multiple saccades. For a significant number of subjects, the proportion of single vs. multiple saccades decreased on target trials at 20 deg and beyond as compared with 10-deg trials (sign test: $p < .001$ for 1-month-olds; $p = .006$ for 2-month-olds). Thus, all subjects showed evidence of multiple saccades at each target distance, and the likelihood of single saccades diminished with increasing target distance from the central fixation stimulus.

Amplitudes of Successive Saccades. It appeared from infant EOG recordings (Figure 5) that the amplitude of each successive potential in a multiple saccade to target was approximately equal.⁸ A variety of post hoc analyses were conducted to allow some conclusions to be drawn as to whether this was the case. First, if this were true, one would expect a greater number of successive saccades in a given multiple saccade series as peripheral target distance from the central fixation stimulus increased. As indicated in Figure 6, when target distance increased from 10 to 20 deg and beyond, the mean proportion of multiple saccades also increased.

However, there did not appear to be any differences in the relative frequency of multiple saccade types on 20-, 30-, and 40-deg trials.

Second, an attempt was made to determine the extent to which linearity in the EOG potential was present for rotation of the infant's eye. We have been assuming that infants, on the average (a) fixated the central fixation stimulus when each trial began, and (b) reached the peripheral target following the execution of a single, or a series of, directionally appropriate saccades. To verify these assumptions, the sum of each subject's EOG potentials in the single or multiple saccade series used to localize the target were obtained for each trial. These sums were averaged across trials by distance for each subject to provide his average total EOG potential change for targets at different distances. For each subject, the average change in potential to a target at 20, 30, or 40 deg was then expressed as a percent increase over his average change in potential to a target at 10 deg. This was done to remove the variability between subjects in the absolute level of EOG potentials. These percentages were then averaged across subjects to provide an indication of the extent to which EOG amplitude was linearly related to eye rotation for infants in the study. Figure 7 shows that the linearity in mean EOG amplitude was the case out to, but not beyond, a 20-deg target distance.

A third analysis was conducted to examine whether the amplitudes of successive saccades in a given localizing series were approximately equal. Since there appeared to be a linear relationship between the EOG potential and amount of eye rotation out to 20 deg from field center, the mean amplitude of each subject's first, second, third, and fourth successive movements in a given multiple saccade were averaged for only 10- and 20-deg trials. Prior to averaging, the amplitude of each saccade in a localizing series was expressed as a percentage of the first saccade in the series. Figure 8 indicates that successive movements

Figure 8. Mean amplitude of second, third, and fourth saccade of a multiple saccade series expressed as a percentage of the first saccade of the series.

were approximately equal in amplitude, with only a slight trend toward decreasing amplitude as the line of sight approached the target.⁹

One might assume from Figure 8 that infants typically moved their eyes a relatively fixed angular distance on each saccade of a multiple saccade series to any target presented within 20 deg of field center. To further evaluate this possibility, we obtained an estimate of the total amount of eye rotation for directionally appropriate saccades to targets at 10 and 20 deg. Each subject's average total EOG potential from initiation to termination of localization was obtained separately for single, double, triple, and quadruple saccades to each target distance. The within-subject averages thus obtained were then averaged across subjects to provide a between-subject average of total change in EOG potential (total eye rotation) for single and multiple saccades to each target. In Table 1, the average total EOG potential change that occurred for each type of localizing saccade series to each target distance is expressed as a multiple of the average total EOG potential change that occurred when the subjects localized a target 10 deg from field center by means of a single saccade. For simplicity, the 10-deg single saccade value was set at unity.

It may be seen from Table 1 that the average total EOG potential to a target at a given distance roughly doubled if a double rather than a single saccade were executed. The results for triple saccades are not an exact triplicate of the single saccade at that distance, but are generally in that direction, i.e., at the very least, values for triple saccades are considerably greater than for double saccades. These results are generally in accord with the notion that the infants generally executed saccades of a fixed amplitude, since it appears from the within-subject summed EOG potential that when double or triple saccades were executed, the eyes rotated considerably farther than when single saccades were executed, at a given distance. Why this should be the case with a seemingly constant initial and terminal position in the field will be later discussed.

However, certain of the findings presented in Table 1 are not consistent with the hypothesis of a fixed amplitude saccadic programming system in the young infant. Specifically, it should be noted that when average summed EOG potentials are compared across rather than within target distances, it is inescapably the case that the infant appropriately increases the amplitude of his single saccadic unit. Thus, a single eye movement to a target at 20 deg was on the average, assuming EOG linearity, twice as large as a single saccade to a target at 10 deg. Similarly, since the average summed potentials for multiple saccades to targets at 20 deg were larger than the summed potentials for multiple saccades to 10 deg, it follows that each of the components within

Table 1
Mean Relative Amplitude of Summed EOG Potentials

Type of Saccade	10-Deg Distance	N	20-Deg Distance	N
Single	1.00	26	2.06	16
Double	1.99	26	2.97	25
Triple	2.76	11	3.55	21
Quadruple			4.81	9

Note—Means indicate the amplitude of the total EOG excursion (eye rotation) per trial relative to the single saccade type on 10-deg trials. N = number of infants.

multiple saccades to targets at 20 deg were larger than components of multiple saccades to targets at 10 deg.¹⁰ In sum, it appears that whereas only saccades of approximately similar average amplitude were executed in a single or multiple series at a given target distance, the size of the saccade unit in both single and multiple saccades increased as target distance increased.

Intersaccade Intervals. Mean intersaccade intervals were calculated between movements in double, triple, and quadruple saccades across all target distances. The mean latency to initiate the first movement of a multiple saccade series was also calculated. However, all latencies to first movement greater than 2 sec were eliminated so that comparisons with later intersaccade intervals would not be biased, since by definition, intersaccade intervals in multiple saccade localizations could not exceed 2 sec. Table 2 presents the mean latencies and intersaccade intervals for double, triple, and quadruple saccades. For all types, the mean latencies to initiate a first saccade were longer than later intersaccade intervals for both 1- and 2-month-olds. Mean intersaccade intervals did not differ by position within a multiple saccade series. Thus, it appeared that once the first directionally appropriate movement was initiated, the latency to initiate further movements in the same direction decreased to a uniform level. A similar effect is noted in adults (Becker, 1972; Becker & Fuchs, 1969; Weber & Daroff, 1971). One-month-olds exhibited consistently longer intersaccade intervals than 2-month-olds ($t = 2.54$, $df = 57$, $p < .01$).

DISCUSSION

The results of this study indicate that young infants are capable of rapidly initiating a saccadic eye movement toward a single extrafoveal target. The first eye movement after peripheral target onset is reliably directionally appropriate to targets as far as 30 deg from the line of sight, but typically grossly hypometric to targets further than 10 deg from the line of sight. Even to a target only 10 deg distant, at least 50% of first localizing saccades are hypometric. Contrary to an earlier report (Tronick, 1972) based on a paradigm in which a central stimulus remained on during

Table 2
Mean Latencies to First Eye Movement and Mean Intersaccade Intervals

Type of Multiple Saccade	Position of Saccade in Series	1 Month Olds			2 Month Olds		
		Latency or Inter-saccade Interval (msec)	N	Number of Trials	Latency or Inter-saccade Interval (msec)	N	Number of Trials
Double	1st	1059	13	60	756	15	74
Double	2nd	526****	13	60	441****	15	74
Triple	1st	934	9	26	886	12	35
Triple	2nd	520**	9	26	453****	12	35
Triple	3rd	514****	9	26	432****	12	35
Quadruple	1st	1133	6	7	923	8	13
Quadruple	2nd	703*	6	7	452**	8	13
Quadruple	3rd	477****	6	7	380***	8	13
Quadruple	4th	527***	6	7	384***	8	13

**t* test indicated that the intersaccade interval was shorter than the initial latency to first saccade, $p < .05$.

** $p < .025$

*** $p < .01$

**** $p < .005$

N = number of infants.

peripheral target presentation, our results indicate that infants can initiate localizing eye movements very rapidly if the central stimulus disappears at the time of peripheral target onset. This latter result corroborates similar findings recently reported by Harris and MacFarlane (1974).

Tronick's data also overestimated the reaction time of the infant saccadic system by including observer reaction time in the mean latency to target localization. He also included trials on which the infant did not direct his *first* eye movement toward the target, but subsequently localized it. We felt (a) that only trials on which the first eye movement was directed towards the target were strong evidence that the target had been detected prior to movement, and (b) that the latency of the first movement was the best estimate of quickest saccadic latency. The resulting latency distributions we obtained were much more variable than typical adult examples in the literature (Komoda et al., 1973; Saslow, 1967; Wheelless et al., 1966), but much of this variability undoubtedly stemmed from our inability to "instruct" the infant as we would an adult. The EOG latency data indicated that despite the infant's higher variability in the time taken to initiate a directionally appropriate saccade, a significant proportion of infant latencies fell within a range of 240 to 500 msec.

Infants exhibited a very large number of directionally appropriate first saccades. However, at least half of these, unlike the adult, were grossly hypometric, and followed by one or more large additional saccades toward target. Could these multiple saccades have been artifacts? First, it could be argued that multiple saccades were an artifact of head restraint. This argument is unlikely because (a) head restraint was minimal, with several infants occasionally exhibiting both head and eye movements, (b) head movements could be detected on the EOG record as a slower potential change usually present as a compensatory movement in the opposite direction to

the initial saccade, (c) multiple saccades were evident at *all* target distances, including 10-deg trials where saccadic eye movements do not typically involve head movements in adults, and (d) adults do not show such grossly hypometric saccades even with severe head restraint. One might argue, however, that infants attempted to program a combination of eye and head movement, but because of immature head control only the eye rotated, causing the undershoots obtained. In this sense, head movement could have affected the results, but in a nonartificial sense.

Second, it could be argued that the infants were not strongly "motivated" to localize the peripheral targets, and lazily jerked their eyes toward target. This argument appears unlikely since first eye movements on over 90% of all 10-deg *replacement* trials were directionally appropriate (see Figure 3), indicative of high interest in the display, *especially* since infants, unlike tired adults, had not been instructed to localize the target. Moreover, at a 10-deg target distance, multiple saccades appeared on approximately 50% of all trials, similar to the incidence on trials at further distances where appropriate localizing response rates were lower. In addition, the linearity of the EOG potential for targets at 10 and 20 deg provides support that these targets were actually looked at (assuming a linear relation between size of EOG potential and amount of eye rotation for ± 20 deg). For the foregoing reasons, it seems most unlikely that the infants were not motivated to localize the targets. This, of course, does not rule out the possibility that the attentional system of the infant was dissimilar from that of the adult because of immaturity, e.g., infants in this study may have been localizing on a more reflex basis.

The data presented in Figure 8 suggested that, for infants, the amplitude of successive saccades within a multiple saccade series was approximately equal. If this were true, one would expect the same number of saccades within a multiple saccade series to be used in

localizing targets at the same distance from the line of sight. However, the large size (approximately 4 deg) of the targets used in the present study (chosen so as to maximize the probability of movement) may have resulted in variation across trials in the number of saccades used to localize a target at the same distance (see Figure 6). For a target at 10 deg, whether a single or whether a double saccade occurred may have been the result of variation in starting and terminal eye position. For example, if the line of sight of an infant was originally at the right- or leftmost contour of the central fixation stimulus and moved either to the left- or rightmost contour (respectively) of a peripheral target 10 deg away, the angular distance of eye excursion would have been either 6 or 14 deg, respectively. Thus, variation in the number of saccades used to localize targets at the same distance may have been at least partially the result of variation in starting and terminal position, a single saccade being executed for shorter starting-terminal distances.

However, it was also found that an infant could increase the size of the unit saccade across target distances, even though the size of the unit remained relatively fixed within a multiple saccade series on a given trial. For example, a given infant could execute two 5-deg saccades to reach a target 10 deg away and also two 10-deg saccades to localize a target 20 deg away. Apparently, a retinal estimate of target distance results in the programming of a distance-related unit of saccade amplitude that is reapplied until the target is localized. Although we were unable to exactly calibrate the infant EOG signal so that it could be converted to visual degrees of eye rotation, our best guess as to the size of the unit saccade of a multiple saccade series would be 6 to 7 deg to targets 10 deg distant and up to 15 deg to targets beyond 10 deg.

It is clear, then, that the infant generally programs and executes a distance-related first saccade to a peripheral target. However, unlike the adult (Becker & Fuchs, 1969; Weber & Daroff, 1971), approximately 50% rather than 90% of the angular distance to target is traversed by the infant's first eye movement. Still more puzzling is the finding that the second eye movement of a localizing series is approximately equal in magnitude to the first. It would appear that the second eye movement is programmed and executed on the basis of the distance between line of sight and target prior to, rather than following, the first movement. The infant appears to reapply a distance-related fixed unit of eye excursion to reach target. However, the fact that normometric first saccades to 10-deg targets occurred with considerable frequency suggests that once the line of sight is within approximately 10 deg or less of target, a more distance-specific terminal movement may be programmed to reach target. Before the foregoing description can be more specifically stated, however,

exact data regarding peripheral localization, where actual starting and terminal positions from the line of sight are objectively specified, are needed.

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REFERENCE NOTES

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NOTES

1. Dayton and Jones (1964) recorded refixation saccades to a moving stimulus of up to 286 deg/sec at 1 month of age.
2. There were significantly different baseline probabilities of movement on *center-on* vs. *center-off* control trials for each axis group (Tukey 99% confidence intervals). In other words, during *center-on* control trials, the subjects typically continued to look at the central fixation stimulus (72% of all trials), while during *center-off* control trials the subjects tended to search the stimulus field, only rarely continuing to look at the empty center of the field (8% of all trials).
3. In absolute terms, probabilities of a directionally appropriate

saccade were consistently much higher on *replacement* than on *addition* trials. However, the high probability of eye movement to either semifield during *center-off* control trials masked this effect. A more stringent response criterion of "directionally appropriate saccade" on all trials, e.g., one in which a location criterion for terminal line of sight was required, undoubtedly would result in a lower *center-off* baseline and a larger *addition-replacement* effect.

4. Signal/noise ratio of the EOG signal varied considerably among subjects. Therefore, only trials on which all three indicators (EOG and both observers) agreed on the direction of first eye movement were used.

5. The results from 40-deg trials are not shown since a directionally appropriate scorable saccade occurred on only 17 such trials.

6. Evidence later presented will support the contention that single saccades were typically normometric to targets within 20 deg of field center.

7. Adults who were placed in the apparatus and instructed to "look at the light that comes on" exhibited only single saccades to target on all 192 trials with no observable corrective movements (see Figure 5f). Of course, it should be recalled that our EOG recording was sensitive only to movements of approximately 2 deg or more, and that peripheral targets were much larger than those used in most adult studies.

8. For adults instructed to localize targets out to 20 deg, such a pattern of equal EOG potentials would indicate a sequence of eye movements of equal rotation. Linearity typically breaks down past 20 deg, but it is easily possible to calibrate the EOG signal for more distance points. However, it was not possible to calibrate the EOG signal of each infant since he could not be instructed to direct his line of sight reliably to known points in the field. In fact, investigation of his ability to do so was the purpose of this experiment. Moreover, there was little reason to expect a priori that the infant's EOG signal was linearly related to eye rotation because of large structural differences between the adult and infant eye. In short, it was unknown whether, or across what excursion, there existed for the infant linearity between the EOG signal and amount of eye rotation.

9. For double saccades on 10-deg trials, first and second saccade amplitudes differed by only 20% or less on 55 of 78 trials. For double saccades on 20-deg trials, first and second saccade amplitudes differed by only 20% or less on 33 of 53 trials. For triple and quadruple saccades on 10- and 20-deg trials, no two saccade amplitudes in a given series differed by more than 20% on 40 of 66 trials. Thus it appeared that the amplitudes of successive saccades in a given multiple saccade series were approximately and consistently equal for targets within 20 deg of field center.

10. It should be recalled that components in a given multiple saccade series were earlier shown to be approximately equal in amplitude (see Figure 8).

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