Peripheral Stimulus Localization by Infants with Eye and Head Movements During Visual Attention

JOHN E. RICHARDS,*† SHARON K. HUNTER*

The effect of attention to a focal stimulus on 14, 20 and 26-week-old infant's peripheral stimulus localization with eye and head movements was examined in this study. Fixation was engaged on a stimulus in the central visual field and a stimulus was presented in the periphery immediately or after a delay. Peripheral stimulus localization occurred less frequently near the beginning of fixation and when a significant heart rate deceleration had occurred (sustained attention), compared with when no focal stimulus was present or after heart rate had returned to prestimulus level (attention termination). Localization was accompanied by head movements on more than two-thirds of the trials, and the likelihood of head movements was positively associated with stimulus eccentricity. The saccades to localize the peripheral stimulus had unusually high velocities in the attention conditions for the two older aged groups relative to their saccades in inattentive conditions. There were unusual "localizing head movements" in the attention conditions in the absence of localizing saccades or changes in fixation for the two older age groups. Infant attention modulates eye movement characteristics of infants. These data also support the hypothesis that eye and head movement systems are relatively independent in the infant, and that eye–head relations during infant attention may be different from during inattention. © 1997 Elsevier Science Ltd

Infants   Eye movements   Heart rate   Attention   Saccades

INTRODUCTION

Peripheral stimulus localization by young infants has been studied for many years. Infants localize stimuli with a combination of eye and head movements, for which the eye movements usually precede the head movements (Regal *et al.*, 1983; Regal & Salapatek, 1982; Roucoux *et al.*, 1982, 1983; Tronick & Clanton, 1971). Head movement initiation probably occurs at the same time as eye movements and the delay of the head movement is due to biomechanical lag (Zangemeister & Stark, 1982). Adult saccades to target eccentricities of less than 20 deg occur without head movements, whereas target localization to larger eccentricities usually involves head movements (Tomlinson & Bahra, 1986a, 1986b). The localizing head movements accompanying the saccadic eye movements center the eye with respect to the head so that eye control muscles do not have to actively hold the orbit at large eccentricities. The relation between head movements and target eccentricity in infant subjects has been informally reported (Regal *et al.*, 1983; Regal & Salapatek, 1982; Roucoux *et al.*, 1982, 1983). It was reported that there was an increase in the number of head

movements accompanying peripheral stimulus localization with increases in eccentricity (3-month-olds, Regal & Salapatek, 1982; 1, 3, and 5 month olds, Regal *et al.*, 1983). Infant subjects often needed multiple saccadic eye movements to localize the targets at the largest eccentricities. Single and multiple head movements may accompany these multiple eye movements. This study examined the effect that attention to a fixated central stimulus had on localizing eye and head movements to peripheral targets in young infants.

There have been three studies of head movements accompanying pursuit eye movements in tracking of visual stimuli (Daniel & Lee, 1990; Roucoux *et al.*, 1982, 1983; von Hofsten & Rosander, 1996), and one study of infants' head and eye movements while viewing a visual field with three-dimensional cubes in specific locations that were static or could rotate in place (Tronick & Clanton, 1971). One of these (Daniel & Lee, 1990) conducted quantitative comparisons of eye and head tracking of moving stimuli or of stationary stimuli when the body was moving. They report an increase in the proportion of head movements from 11 to 16 weeks, and increases in measures of head/eye tracking accuracy (gain, lag, gaze velocity error) from 11 to 28 weeks.

There are few studies systematically investigating saccade characteristics in young infants. Aslin & Salapatek (1975) reported that infants of 1- and 2 months of age often showed a series of fixed amplitude

*Department of Psychology, University of South Carolina, Columbia, SC 29208, U.S.A.
†To whom all correspondence should be addressed [*Fax*: +1-803-777-9558; *Email*: richards-john@sc.edu].

hypometric saccades to the peripheral stimulus. These step-like saccade sequences diminished in frequency if the peripheral stimulus was extinguished after the first saccade (Salapatek et al., 1980). The relation between saccade velocity and amplitude (or duration and amplitude, the "main sequence"; Bahill et al., 1975), has not been studied for peripheral stimulus localization. The only detailed published study of the main sequence relation in infants is by Hainline et al. (1984). They recorded eye movements with corneal reflection procedures while infants were viewing complex and simple visual scenes. They found adult-like main sequence relations in infants during scanning of interesting (i.e., complex) visual scenes, but a decrease in the peak velocity/amplitude slope for uninteresting (i.e., simple) visual scenes. The decreased slope represents slower speeds per degree of saccade eccentricity, and was interpreted as representing a lack of interest. This study suggests that processes such as attention or arousal can affect the basic brainstem mechanisms thought to be responsible for the main sequence relation. Some studies of main sequences in infants during peripheral stimulus localization have been done and reported in conference abstracts (e.g., Regal & Salapatek, 1982; Ashmead, 1984; see Regal et al., 1983), but details of those studies are not available.

The effective field to which infants will localize a peripheral stimulus is diminished in the presence of a central stimulus. For example, Aslin & Salapatek (1975) found that the eccentricity to which localization would occur was much smaller in the "competitive" situation with a central and peripheral stimulus than when there was no central visual stimulus or when the central stimulus disappeared prior to or simultaneous with peripheral stimulus onset (Aslin & Salapatek, 1975; cf. Harris & MacFarlane, 1974; MacFarlane et al., 1976; Tronick, 1972). One- and 2-month old infants make directionally appropriate eye movements towards a peripheral stimulus at 40 deg more than 50% of the time without a central stimulus, but less than 20% of the time in the focal central stimulus' presence (e.g., Aslin & Salapatek, 1975). Focal stimulus presence by itself is not the factor affecting the attenuated localization. Using heart rate changes known to be associated with infant attention or inattention, it has been shown that the probability of detecting a peripheral target of limited duration is lower if the infant is attending to a central visual stimulus than when inattentive fixation is occurring (Finlay & Ivinskis, 1984; Hicks & Richards, 1996; Richards, 1987, 1997). When a central stimulus is present but attention is unengaged, then peripheral stimulus localization occurs at latencies and with probabilities similar to the non-competing situation when the central stimulus is absent.

This study had two goals. The first goal was to examine how head movements were used in localization of peripheral stimuli, and if attention to a central stimulus affected head movements. Infants were tested at 14, 20 and 26 weeks of age (3, 4.5 and 6 months). An interesting

visual stimulus was presented in the infants' focal visual field. Peripheral stimuli at eccentricities of 25, 35 or 45 deg were presented after a delay. The experimental conditions maintained to result in differing attention levels were: the peripheral stimulus presented after focal localization of a simple blinking dot; the focal and peripheral stimulus presented simultaneously; the peripheral stimulus presented after a 2 sec delay; the peripheral stimulus presented after a significant heart rate deceleration; or the peripheral stimulus presented after heart rate returned to its prestimulus level after a significant deceleration. The simultaneous, 2 sec delay, and heart rate deceleration delay conditions represent attention engagement to the focal visual stimulus, whereas the return of heart rate to its prestimulus level represents inattention, and the simple blinking dot is prior to attention engagement (Berg & Richards, 1997; Richards, 1997; Richards & Casey, 1992). This aim of the study was a descriptive one to determine the probability of head movements accompanying localization, and to determine if head movements accompanying localization were affected by attention to the focal stimulus.

The second goal was to examine the characteristics of the saccadic eye movements occurring during attention, and in relation to head movements. The characteristics of saccades to peripheral stimuli have not been reported in infants in this age range, and some saccade characteristics (e.g., velocity–amplitude relation) have not been reported in infant peripheral stimulus localization. Since it is known that attention affects localization latency and probability, the suggestion that the main sequence relation is affected by attention level in infants (Hainline et al., 1984) was examined in a localization paradigm. Adult's saccades occurring during head movements have slower velocity, or a depressed velocity–amplitude slope, relative to saccades occurring with the head fixed (Tomlinson & Bahra, 1986a). Thus, the characteristics of the saccades in the head-free condition may vary depending on head movement. Finally, recent models of neural systems controlling infant eye movement during attention (Berg & Richards, 1997; Johnson, 1990, 1995; Richards & Casey, 1992; Richards & Hunter, 1998) hypothesize that there is an increasing tendency of foveal processing pathways in the brain to inhibit reflexive saccades to peripheral stimuli in this age range. This study should show the changing relation from 3 to 6 months of age between attention directed towards a central stimulus and the characteristics of eye movements to peripheral stimuli.

METHODS

Participants

Infants were recruited from birth notices published in a Columbia, South Carolina newspaper. The infants were full term, defined as having birthweight greater than 2500 g and gestational age of 38 weeks or greater based on the mother's report of her last menstrual cycle. The

infants had no acute or chronic pre- or perinatal medical complications and were in good health at the recording session. There were 89 infants sampled cross-sectionally at 14 (N = 32, M = 99.6 days, SD = 4.33), 20 (N = 28, M = 140.6 days, SD = 4.43), or 26 (N = 29, M = 183.3 days, SD = 3.85) weeks postnatal age. The delay of the peripheral stimulus (see *Procedure*) was a between-subjects factor, with between five and eight subjects of each age in the five delay conditions. An additional 22 infants were tested but did not complete the minimum number of trials (fussy, missing data, experimental protocol errors) and were not included in the analyses.

Apparatus

The infant was held in his/her parent's lap approximately 51 cm from the inner edges of two black and white 49 cm (19 in) TV monitors. Each screen's center was 56 cm from the infant's eyes and the far edge was 70 cm. The TVs' plane was parallel to the infant's eyes. The TVs subtended 88 deg visual angle, with one TV subtending 44 deg visual angle. There was a visual angle of 48 deg from each monitor's center. A neutral color material covered the surrounding area. A video camera was centered and above the TVs. An observer judged infant fixations on a TV monitor in an adjacent room. The session was recorded on videotape with a time code in order to synchronize physiological and experimental information for analysis.

There were three types of stimuli used for the experimental trials. A 1 deg × 1 deg white square that blinked on and off was used to attract the infant's initial fixation. This was placed on one TV and centered at 15 deg from the edge of the TV near the center of the testing apparatus. The focal stimuli were computer-generated patterns shown on the TV monitor (e.g., a series of computer-generated concentric squares of varying size, a flashing checkerboard pattern, a small box shape moving across a diamond; 12 different patterns). The stimuli were presented in a 10 cm square area, subtending approximately 10 deg visual angle. The focal stimuli were centered in the same location as the blinking square. The peripheral stimulus consisted of a 3 deg wide × 6 deg high square that changed black–white shading dynamically in a sinusoidal pattern. The peripheral stimulus was presented on the adjacent TV centered vertically, even with the focal stimulus. It was intended that the peripheral stimulus be presented at 25, 35 or 45 deg eccentricities. Based on the actual distance measured during the experiment of the infant from the TV displays, the peripheral stimulus presented averaged 25.96, 36.33 and 42.40 deg (0.453, 0.634, and 0.739 radians, respectively) measured from the center of the focal stimulus.

Measurement and quantification of heart rate

The electrocardiogram was recorded with Ag–AgCl electrodes placed on the infant's chest. The ECG was digitized on-line at 1000 Hz (1 msec). The R-wave of the ECG was identified and interbeat intervals were com-

puted. The interbeat intervals were computed within 1 msec of the R-wave occurrence for the on-line evaluation of heart rate changes. The delay for the "heart rate deceleration" condition occurred following a significant heart rate deceleration, evaluated on-line as five successive beats with inter-beat-intervals, each longer than the five prestimulus beats' median (i.e., sustained attention; Richards, 1987, 1997). The delay for the "heart rate acceleration" condition occurred when heart rate returned to its prestimulus level, evaluated on-line as five beats with inter-beat-intervals shorter than the five prestimulus beats' median (i.e., attention termination; Richards, 1987, 1997). An examination of the interbeat intervals showed that the manipulation resulted in the appropriate heart rate change (e.g., Richards, 1987, Fig. 1; Richards, 1997, Fig. 2).

Procedure

The parent sat in a chair in the viewing area with the infant on the parent's lap facing the TV monitors. There were five experimental conditions: prestimulus, immediate, 2 sec, heart rate deceleration, heart rate acceleration. Each experimental trial began with the presentation of the blinking dot on one of the TVs until the infant looked toward the dot. The blinking dot on the "prestimulus" condition was turned off (replacement) or left on (addition) and a peripheral stimulus was presented on the adjacent TV for 2 sec. For the other conditions, a "focal" stimulus was presented in place of the blinking dot, and the peripheral stimulus onset was presented for 2 sec at predetermined delays. The "immediate" condition was an immediate replacement/addition of the focal stimulus with the peripheral stimulus. The "2-sec" condition consisted of a 2 sec delay between the onset of the focal stimulus and the replacement of/addition to the focal stimulus with the peripheral stimulus. The "heart rate deceleration" condition consisted of the focal stimulus onset until a heart rate deceleration, and then the replacement/addition of the focal stimulus with the peripheral stimulus. The "heart rate acceleration" condition delay occurred when heart rate returned to its prestimulus level following a heart rate deceleration. If the infant looked toward the peripheral stimulus while it was on (or within 1 sec of its being turned off) the focal stimulus was turned off and the peripheral stimulus remained on for 5 sec. Otherwise, the focal stimulus remained on for 2 sec after the offset of the peripheral stimulus. A minimum 5 sec inter-stimulus interval occurred between each trial.

There were two within-subjects factors in the experiment: eccentricity (and control), and replacement/addition. Each infant received peripheral stimulus presentations at nominal eccentricities of 25, 35 and 45 deg. A control condition was included in which the delay condition protocol was followed but no peripheral stimulus was presented. There were equal numbers of "replacement" and "addition" trials, in which the focal stimulus was turned off when the peripheral stimulus came on (replacement) or the focal stimulus remained on

when the peripheral stimulus came on (addition). The three eccentricities and control trials were each done as replacement or addition trials, resulting in eight trial types. These trial types were presented randomly without replacement in eight-trial blocks. Each infant received a minimum of two of the eight trial types.

Testing was done only if the subjects maintained an alert, awake state during the entire procedure (eyes open, no fussing or crying, responding to the protocol). The heart rate-defined delay trials were restarted if no heart rate deceleration occurred within 10 sec following fixation onset. They were also restarted if the infant looked away from the TV before heart rate returned to the prestimulus level or was not looking when the peripheral stimulus was to be presented. After every eight experimental trials, a recording of a Sesame Street movie was shown on both TVs for approximately 10 sec. This was followed by the presentation of a "focal stimulus" simultaneously on each of the TVs for 5–10 sec. These presentations were included to prevent the association of temporal sequencing between the focal and peripheral stimuli and were used to adjust the EOG recording, but were not included in any of the analyses.

Peripheral stimulus localization judgments

A single observer judged the infant's fixation direction during the experiment in an adjacent room on a TV monitor in order to control the experimental protocol. Each session was judged offline. A time code recorded on the videotapes allowed the judgment to have millisecond accuracy, though resolution was limited to a single video frame scan ($\frac{1}{2}$ total frame length = ~ 16 msec). The observer judged the looks during the trials as: looking at the stimulus on the right TV, looking at the stimulus on the left TV, or looking away. The videotape time code was used by the computer to determine what part of the experimental protocol was occurring (interstimulus interval, blinking square, focal stimulus, peripheral stimulus). The offline judgments were used to assess the integrity of the experimental protocol and if a peripheral stimulus localization occurred. The judgment of the localization gave the approximate time of the localization that aided in the identification of saccades used to localize the peripheral stimulus.

Measurement and quantification of head movements

The infant's head movements were quantified in two manners. First, a small dot was placed on the infant's forehead above the right eye. The videotape recording was played through a frame-grabber on the computer monitor, and a cursor was placed over the small dot with a computer-pointing device (mouse). The videotape from the onset of the peripheral stimulus for 3.5 sec following it was advanced by half-frames ($\frac{1}{2}$ total frame length = ~ 16 msec). The location of the computer-pointing device was recorded (pels).

The absolute eccentricity of the head relative to the center of the TVs was calculated according to a "head movement geometry". Head size parameters (e.g.,

nasion–inion distance, nasion–mastoid circumference, mastoid–inion circumference, mastoid–mastoid distance) were measured on each infant in order to calculate the mastoid–mastoid nasion–inion intersection, which is the approximate axis of head rotation (Kapandji, 1974; Warfel, 1985). The rotation of the head around its axis was calculated according to a horizontal, planar geometry (Hine & Thorn, 1987; Wist *et al.*, 1983). The absolute eccentricity of the head spot relative to the center of the TVs could be calculated from the distance of the head to the plane of the TVs, the rotation of the head around its axis, the known distances between the stimuli on the plane of the TVs, and the pels of the head spot on each frame. Thus, the pels of head movement could be translated into degree coordinates for the head position for each 16 msec interval.

Head movements were verified with electromyogram (EMG) recording from the sternocleidomastoid muscle of both sides of the neck. These muscles are agonists for contralateral head movement and stabilize the head against the lateral pull of the splenius muscles which perform the flexor movement for horizontal head movements (Warfel, 1985). Bipolar recording of EMG muscle activity was done with 6 mm Ag–AgCl electrodes placed on the infant's neck just under the mastoids on both sides. The EMG was digitized on-line at 1000 Hz (1 msec). The EMG was amplified at 20 K and was filtered from 10 to 300 Hz. The RMS of the digitized EMG values were calculated over 10 msec epochs. Ipsi- and contralateral EMG were examined for each head movement identified in the videotape recording that occurred between the peripheral stimulus onset and offset, for activity with an onset 500 msec before or after the beginning of the video-judged head movement. The onset and offset of the EMG activity and the peak RMS amplitude were recorded for each head movement.

Measurement and quantification of saccades

The electrooculogram (EOG) was recorded with 6 mm Ag–AgCl electrodes placed posterior to the external canthus of each eye. The EOG was digitized on-line at 1000 Hz (1 msec). The EOG was amplified at 2 K and a DC-recording was made. The saccades were separated from the composite EOG record with an algorithm presented in Matsuoka & Ueda (1986; Matsuoka & Harato, 1983). This algorithm uses a third-order differential equation to identify saccades. A computer-based editing program was used to confirm the algorithm identification and select the onset and offset of the saccade. The velocity of any smooth pursuit component in the composite EOG record was estimated from the velocities preceding and following the saccade, and a smooth pursuit component signal was interpolated between the beginning and end points of the saccade. Finally, the difference between the interpolated smooth pursuit signal and the composite signal was the resultant saccadic component. There was no velocity change in the composite signal for most peripheral saccades before or after the saccade because fixation was steady on the focal

or peripheral stimulus. Saccades were quantified through-out the experimental session. The onset–offset of the saccade was recorded, the maximum velocity of the saccade during its occurrence, and the EOG amplitude (μV) at the beginning and end of the saccades.

Peripheral stimulus localization, as judged by the videotape recording, was quantified with the saccade onset. A saccade in the direction of the peripheral stimulus after its onset, not preceded by other saccades, and judged as a localization on the videotape recording, was defined as a localization. "Compensatory ocular responses" were quantified in the EOG record. If the eyes retain fixation on a stimulus and a head movement occurs, the eyes shift in the orbit as the head moves, leading to a change in EOG in the direction opposite the head movement. Similarly, during head shifts towards a peripheral stimulus the head may continue rotating for some time after the target has been localized, and the vestibuloocular reflex (VOR) holds the gaze stable (Guitton, 1991, 1992; Guitton et al., 1990; Tweed et al., 1995). The VOR is inhibited during most of the saccade even though the head is moving, and begins to affect the eye trajectory only as the gaze nears the target (Guitton & Volle, 1987; Pelisson et al., 1988; Tomlinson, 1990; Tomlinson & Bahra, 1986b). The onset, offset, maximum velocity, and EOG amplitude of the compensatory ocular response was identified for any head movement that occurred from peripheral stimulus onset through 3.5 sec following onset.

The amplitude of saccades was calibrated by using the blinking dot fixation and peripheral stimulus fixation as fixation points, and by estimating b-weights for each infant for the relation between EOG electrical potential and degree of eye rotation in the orbit (Finocchio et al., 1990; Woestenburg et al., 1984). The fixation points for the saccades were the blinking dot (1 deg horizontal) and the peripheral stimulus (3 deg horizontal) obtained from the experimental procedure, rather than using a pre-experimental calibration procedure. The degree difference between fixation on the blinking dot and peripheral stimulus was calculated on each peripheral stimulus trial. The EOG measures the eye position relative to the head, so the rotation of the eyes in the orbit is proportional to the EOG signal. On trials without head movements, the difference between the electrical potential of the EOG for the fixation on the blinking dot and the peripheral stimulus was used and the degree difference between the stimuli was used. On trials with head movement, the degree of eye movement is not simply the difference between head location and peripheral stimulus eccentricity, as has been done with studies of infant head movement (Daniel & Lee, 1990; Regal et al., 1983; Roucoux et al., 1982, 1983). The eye–head–stimulus relation must be calculated with a horizontal planar geometry because of the forward and lateral displacement of the axis of eye rotation relative to the axis of head rotation (Hine & Thorn, 1987; Wist et al., 1983; von Hofsten & Rosander, 1996). Eye eccentricity relative to head position can be computed directly, given head

eccentricity relative to the fixated stimulus, the radius of the head rotation, and the distance to the stimulus. The degree of the eye rotation in the orbit necessary to fixate the blinking dot or peripheral stimulus was calculated, along with the difference in EOG μV values for these fixations. These EOG μV/deg measurements were taken for each fixation at the beginning, middle, and end of the fixation. The degree and uncalibrated EOG μV differences were regressed separately for each infant to provide a b-weight relating electrical potential shifts to degree change (radians per μV) (see Finocchio et al., 1990; Harris et al., 1981; Woestenburg et al., 1984). The regression was done iteratively with irregularly large prediction errors (predicted minus actual) discarded until the errors converged to a reasonably small and stable level (Harris et al., 1981). Each saccade amplitude representing a potential difference was multiplied by this b-weight to obtain the degrees of saccade amplitude. The average error for relating the calculated degree measurements based on the EOG to the actual degree measurement involved in eye rotation was 0.0353 radians (2.02 deg, SD = 0.0612, 90 P = 0.1325 radians). The error for gaze degree (eye and head together) was similar to that of eye movements alone, since head position could be calculated directly (M = 0.0366 radians, SD = 0.0624, 90 P = 0.1372). The relation between actual and calculated eye movements was linear (R^2 = 0.9862, P < 0.0001).

This calibration used the eye movements during the experiment rather than using a separate calibration sequence. Calibration of eye movements for infants may take as long as 10 min (e.g., Finocchio et al., 1990), but only 10–20 min is usually available to test infant subjects before becoming fussy. The use of the experimental data for calibration follows that of other researchers testing infant subjects (e.g., Aslin & Salapa-tek, 1975; Daniel & Lee, 1990; Salapatek et al., 1980; Shea & Aslin, 1990). The horizontal size of the blinking dot (1 deg) and peripheral stimulus (3 deg) limits the resolution and accuracy of the eye movement for specific accuracy. These sizes are similar to those used by other researchers with infant subjects (e.g., 1.7 deg in Finoc-chio et al., 1990; 2 deg in Shea & Aslin, 1990, and in Salapatek et al., 1980; 4 deg in Aslin & Salapatek, 1975; 6.8 deg in Reisman & Anderson, 1989; 7.2 deg in von Hofsten & Rosander, 1996; 7.7 deg in Daniel & Lee, 1990). The actual degrees of eye movement were used only for the main sequence analysis. In that analysis, the velocity and amplitude of the eye movement are taken from EOG (μV) values in the same eye movement. Thus, the translation from EOG to degrees would be done on data taken from the same eye movement so that a constant would be multiplied by both terms for the main sequence regression (e.g., velocity, amplitude) and the same regression patterns (b-weights, polynomial degree) should occur. Additionally, any residual errors should appear on both sides of the regression equation and should not contaminate the estimates of slope (Hainline et al., 1984). Thus, the analysis of the raw analog-to-
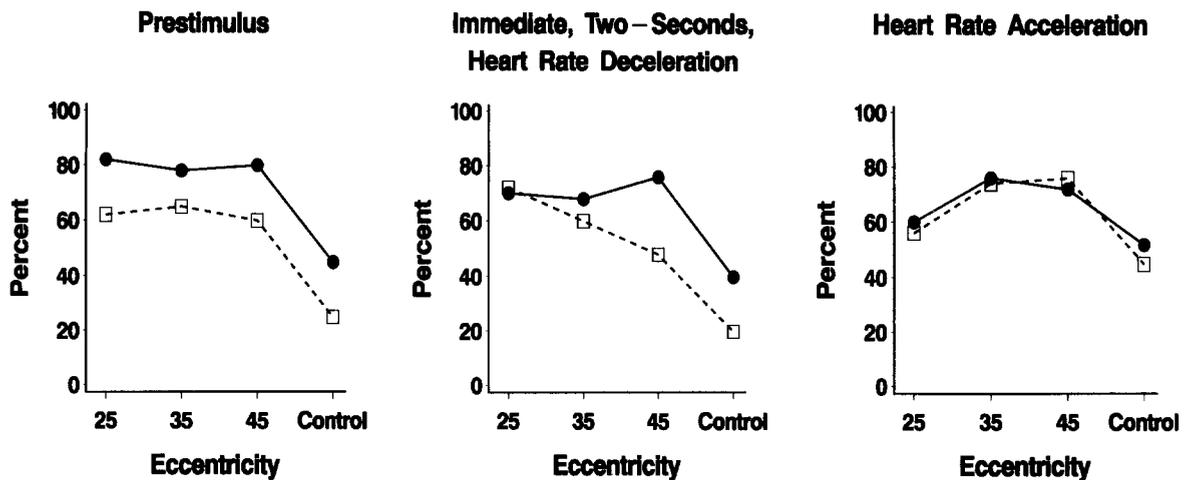
FIGURE 1. Percentage of peripheral stimulus localization as a function of addition (dashed lines and open squares) and replacement trials (solid line and filled circles), experimental conditions, and stimulus eccentricity. The experimental conditions thought to be attention-engaging are combined (immediate, 2 sec, heart rate deceleration) because age and eccentricity relations were similar for those three trials.

digital or μV values would result in identical fit estimates and level of the polynomial equation. The actual degrees amplitude and velocity relations for the main sequence analysis should be taken with respect to the measurement error inherent in the calibration procedure.

Experimental design for statistical analysis

The experimental factors for the statistical analyses included the between-subjects factors of age (3; 14, 20, 26 weeks) and delay (5; prestimulus, immediate, 2-sec, heart rate deceleration, heart rate acceleration). The repeated measures factors were stimulus eccentricity (4; control, 25, 35 and 45 deg) and focal stimulus presence (2; addition, replacement). Most of the analyses involved categorical variables (e.g., localization/non-localization) and were analyzed with log–linear categorical modeling.

RESULTS

Probability of peripheral stimulus localization

Localization percentage. The localization of the peripheral stimulus was examined in relation to the experiment factors. Figure 1 shows the localization percentage for the experimental conditions as a function of the addition/replacement and eccentricity/control factors. There were two main findings that are shown in Fig. 1. First, a "competition" effect occurred in that peripheral stimulus localization on the addition trials occurred less frequently (52.8%, $N = 766$) than on the replacement trials (65.1%, $N = 769$), χ^2 (1, $N = 1535$) = 22.15, $P < 0.0001$. Second, Fig. 1 shows a decreasing localization percentage across eccentricities for these: the immediate, 2-sec, and heart rate deceleration conditions on the addition trials, χ^2 (2, $N = 786$) = 7.06, $P = 0.0292$. The replacement trials did not differ in localization percentage across the eccentricity levels.

The age factor interacted with several of the experimental factors (e.g., Age × Delay × Eccentricity ×

Addition/Replacement, χ^2 (24, $N = 1535$) = 57.53, $P < 0.0001$). The 14-week-old infants showed a significant Addition/Replacement main effect for all experimental conditions. This was the "competition" effect in which peripheral stimulus localization on the addition trials occurred less frequently than on the replacement trials. The 20-week-old infants showed the same effect for the prestimulus, immediate, 2-sec, and heart rate deceleration conditions, and the 26-week-old infants showed this effect for the prestimulus conditions. For the immediate, 2-sec, and heart rate deceleration conditions, the 26-week-old infants had the same localization percentage for addition and replacement trials for the smallest two eccentricities, and showed the competition effect for these conditions only at the largest eccentricity. Finally, both the 20- and 26-week-old infants reversed this effect on the heart rate acceleration trials, and actually had in this condition a larger localization percentage for the addition trials (76.0%, $N = 75$) than the replacement trials (62.2%, $N = 74$).

Head movements accompanying localization. The trials on which head movements accompanied localization were examined. Localizations were divided into two categories: (1) no head movement necessary to achieve the localization as judged offline, and by the non-overlap of the saccade onset/offset and any head movement on that trial; (2) head movement occurring in advance of the peripheral stimulus localization as judged offline, and by the overlap of localizing saccades and head movements. Table 1 shows the number of peripheral stimulus presentations, overall percentages of localizations, and the percent of localizations with and without head movements, as a function of the experimental conditions. Over two-thirds of the localizations were accompanied by head movement. The proportion of trials with head movements differed across the delay conditions, χ^2 (4, $N = 824$) = 37.21, $P < 0.0001$. The largest proportion of trials with head movements were found on the prestimu-

TABLE 1. Localizations with and without accompanying head movements on peripheral stimulus (PS) present trials, as a function of delay conditions

	Prestim	Immediate	2-sec	HR Dec	HR Acc	All types
Number of PS trials	144	200	184	165	141	824
PS localization	78.3%	66.3%	83.3%	76.4%	80.9%	75.9%
Saccade only	25.7%	38.5%	20.6%	48.5%	29.0%	32.7%
Saccade and head movement	74.3%	61.5%	79.4%	51.5%	71.1%	67.3%

Prestim, prestimulus; HR Dec, heart rate decelerating; HR acc, heart rate accelerating.

lus, 2-sec, and heart rate acceleration trials. The immediate and heart rate deceleration conditions had the fewest head movements (Table 1). As might be expected, the proportion of trials with head movement increased with increasing eccentricity (25 deg, 60.8%, $N = 276$; 35 deg, 66.1%, $N = 272$; 45 deg, 74.6%, $N = 276$), χ^2 (2, $N = 824$) = 8.89, $P = 0.0117$.

The temporal relation of the saccades, contralateral EMG activity onset, and video-judged head movements was examined for the trials on which the peripheral stimulus was localized (Zangemeister & Stark, 1982.)* The largest proportion of trials had both EMG activity and head movements preceding saccadic eye movements (39.6%, $N = 824$). A second temporal relation consisted of the onset of contralateral EMG activity, a saccade in the direction of the peripheral stimulus, followed by a

*The head movement characteristics (onset following peripheral stimulus, duration, and size of video-based movements, and onset, peak and time of peak for contralateral and ipsilateral EMG) were examined to insure there were no effects of the experimental factors on head movement. The average onset of the EMG activity on the contralateral side occurred 68.4 msec before the video-judged head movement and had its peak RMS activity at 338.2 msec after the video-judged head movement. The corresponding values for the ipsilateral activity were 73.1 msec for EMG activity onset and 311.5 msec for peak RMS EMG. The head movement characteristics (onset following peripheral stimulus, duration, and size of video-based movements, and onset, peak and time of peak for contralateral and ipsilateral EMG) were analyzed with an Age (3) × Delay (5) × Addition/Replacement (2) × Eccentricity (3) ANOVA[1a]. The eccentricity factor affected the size of the video-judged head movement, $F(2,106) = 6.45$, $P = 0.0023$, the peak EMG activity of the contralateral muscle, $F(2,107) = 5.35$, $P = 0.0061$, and the time of the peak contralateral EMG activity, $F(2, 114) = 4.88$, $P = 0.0099$. As expected, there was an increasing distance of the head movement with increasing eccentricity (average radians = 0.443, 0.530, and 0.563 for the 25, 35, or 45 deg eccentricities, respectively). The peak RMS activity increased for the three eccentricities (12.44, 13.38, and 17.45 RMS μV, respectively). The peak RMS occurred increasingly later with increasing eccentricity (293.2, 329.5, and 386.3 msec following the video-judged head movement). There were no significant effects on the ipsilateral EMG times or peak activity, and no significant effects of the delay, age, or addition/replacement factors.[1a]This analysis had missing data for subjects primarily because not all subjects shown, showed head movements on all trials, so all Delay × Addition/Replacement × Eccentricity × Subjects cells were unfilled, or unequal numbers of data were in each cell. Because of the missing cells, the ANOVAs were computed with a general linear models approach using non-orthogonal designs. The sums of squares (hypothesis and error) for the nested effects in the design were estimated using "subjects" as a class and nesting repeated measures (intervals, delay types) within this class variable. The "PROC GLM" of SAS was used for the computations.

head movement towards the peripheral stimulus (19.5%, $N = 824$). The third temporal relation began with a saccade in the direction of the peripheral stimulus, followed by EMG activity or head movements that overlapped one or more of the saccades (18.9%, $N = 824$). The rest of the localization trials consisted of saccades without any EMG activity or head movements, or the EMG/head movements occurred following all saccadic eye movements (21.8%, $N = 824$).

Head movements without localization. It was observed on several trials that during fixation on the focal stimulus, closely following the onset of the peripheral stimulus, the infant's head would move in the direction of the peripheral stimulus while the eyes (and fixation) remained fixed on the focal stimulus. It appeared the infant was "trying" to localize the peripheral stimulus but was unable to break fixation on the focal stimulus. These trials were identified by four criteria: (1) fixation was judged offline to continue on the focal stimulus and the peripheral stimulus was missed; (2) there was no saccade in the direction of the peripheral stimulus; (3) there was a head movement identified in the videotape recording, that was accompanied by appropriate EMG neck muscle activity; (4) there was a compensatory ocular response in the EOG signal to show that fixation continued on the focal stimulus. Seventy-seven trials were identified that met these criteria. This number of trials represents 38.6% of the trials on which peripheral stimulus localization did not occur ($N = 199$). The head movement characteristics (onset following peripheral stimulus, duration, and size of video-based movements, and onset, peak and time of peak for contralateral and ipsilateral EMG) were examined and most were similar to those found with head movements accompanying localization. The only striking exception was that head movement size was smaller (head movement size with saccadic localization, $M = 0.510$ radians, head movement size without saccadic localization, $M = 0.365$ radians). These characteristics could not be examined with ANOVA because the small number of observations did not allow the use of a factorial design for the analysis (age, delay, addition/ replacement, eccentricity factors).

The frequency table for the head movements that occurred without visual localization was examined.† The only significant factor was the experimental delay factor,

†The categorical variable and the factorial design for this analysis did not have sufficient data (empty cells or cells with very small numbers) to analyze the full factorical design. Therefore, only the main effects and two-way interactions were analyzed.

TABLE 2. Localizations for single saccades and multiple saccades on
peripheral stimulus present trials, as a function of testing age

	14 weeks	20 weeks	26 weeks	All subjects
Total number of localizations	290	268	266	824
Single saccade	45.2%	54.7%	67.9%	55.6%
Two saccades	44.5%	38.2%	27.2%	36.9%
Three saccades	10.3%	7.1%	4.9%	7.5%

χ^2 (4, N = 77) = 10.93, P = 0.0274. The percentage of head movements occurring without saccadic localization was smallest for the prestimulus and heart rate acceleration conditions, and larger for the immediate, 2-sec, and heart rate deceleration conditions (prestimulus, 14.2%; immediate, 23.3%; 2-sec, 23.3%; heart rate deceleration, 31.1%; heart rate acceleration, 7.7%). Post hoc tests showed that the number of these head movements occurring in the prestimulus and heart rate acceleration conditions were not significantly different, but both were significantly less than the immediate, 2-sec, and heart rate deceleration conditions.

There were two age differences in these head movements that occurred without localization that were interesting (though not statistically significant). Compared with the non-localization trials on which there was no head movement, there was an increase over age in the number of head movements that occurred without localization (percent head movements without localization, 14 weeks, 18.5%, N = 113; 20 weeks, 36.4%, N = 74; 26 weeks, 39.1%, N = 74). There also was an increase over the three ages in the percent of trials that occurred in the three "attention" conditions (immediate, 2-sec, heart rate deceleration) compared with the total number of these types of head movements (trials occurring in immediate, 2-sec, and heart rate deceleration, 14 weeks, 71.5%, N = 21; 20 weeks, 77.8%, N = 27; 26 weeks, 82.9%, N = 29).

Characteristics of localizing saccades

Multiple saccades. The localization of the peripheral stimulus was done by the infants with a single saccade or multiple saccades. Table 2 shows the proportion of trials with a peripheral stimulus in which localization occurred with a single or multiple saccade. Table 2 shows a decreasing number of multiple saccades over the three testing ages, χ^2 (2, N = 824) = 32.72, P < 0.0001. As might be expected, there was an increasing use of multiple saccades for localization as eccentricity increased (percent multiple saccades, 25 deg, 38.8%, N = 276; 35 deg, 45.2%, N = 272; 45 deg, 49.4%, N = 276; χ^2 (2, N = 824) = 7.43, P = 0.0243).

Aslin & Salapatek (1975; Salapatek et al., 1980) reported that multiple saccades of 1- and 2-month old infants were of fixed amplitude and hypometric. The amplitudes of the multiple saccades were examined. "Hypometric saccades" were defined as those multiple saccades for which the saccade amplitudes were within 20%. Other saccades were defined as "corrective saccades", that is, the saccades were greater than 20% different in size. This type of saccadic pattern is assumed to represent an initial attempt to localize the stimulus, followed by a recomputation of the target position, and a corrective saccade. The large majority of the multiple saccades were of the localizing–corrective type (78.9%, N = 364), and a small number of hypometric saccades were found (21.2%, N = 364). The absolute number of hypometric saccades (N = 77) was 12.3% of the total number of peripheral stimulus localizations (N = 625). There was a decreasing amount of hypometric saccades over the three ages (percent hypometric saccades, 14 weeks, 25.3%, N = 158; 20 weeks, 18.1%, N = 121; 26 weeks, 17.6%, N = 85). The corrective saccades usually consisted of a large initial saccade followed by a smaller corrective saccade (70.3%, N = 287). Small saccades followed by a large saccade occurred less frequently (29.7%, N = 287). There was a difference in three ages in these proportions. The youngest two ages had a higher proportion of the corrective saccades with the "localizing–corrective" sequence than did the 26-week-old infants (corrective saccades with "localizing–corrective" sequence, 14 weeks, 75.4%, N = 118; 20 weeks, 71.7%, N = 99; 26 weeks, 60.0%, N = 70).*

Main sequence. The "main sequence" (Bahill et al., 1975) is a lawful relation between maximum saccade velocity and saccade amplitude, or saccade duration and saccade amplitude. A polynomial regression model was developed on saccades found in the prestimulus period. This model was then tested for its fit to saccades occurring in parts of the experimental trials. This was done to compare the saccades in the "inattentive" prestimulus period with the saccades when attention may have been directed to the focal stimulus. The regression parameters developed for the prestimulus saccades provided a satisfactory fit for the first saccade from the blank field to the blinking dot at the beginning of the experimental protocol, and the saccades to the peripheral stimulus in the prestimulus and immediate experimental conditions. In the conditions in which attention was already engaged (2-sec, heart rate deceleration), the polynomial regression model developed on the "inattentive" saccades in the prestimulus period fit the empirical data poorly.

The saccades identified in the prestimulus recording period were selected and a polynomial regression equation was estimated. The relation between maximum

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*A hypometric/corrective multiple saccade categorical dependent variable was analyzed with an Age (3) × Delay (5) × Eccentricity (3) × Addition/Replacement (2) design with linear categorical modeling[2]. None of the experimental factors significantly affected the distribution of hypometric and corrective saccades. Thus, although the age differences in the proportion of hypometric saccades is suggestive, the statistical tests of its distribution are nonsignificant (probably due to small N and low power of test). Similarly, the age difference on the corrective saccade sequence ("localizing–corrective") was not statistically significant, probably owing to a small N and low power of the statistical test.

TABLE 3. Main sequence relation multiple regression coefficients for third-order polynomial equations, for the different components of the experimental procedure†

Experimental procedure	N	Multiple R^2		Polynomial coefficients		
		R^2 from prestimulus b-weights	R^2 from estimated b-weights	b_{linear}	$b_{quadratic}$	b_{cubic}
Prestimulus	2119	0.666	—	0.0370	−0.0604	0.0400
Blinking dot	1080	0.687	0.692***	0.0366	−0.0525	0.0304
All PS localizations	1283	0.650	0.655**	0.0374**	−0.0575	0.0357***
Experimental conditions						
Prestimulus	243	0.750	0.753	0.0303	−0.0392	0.0242*
Immediate	289	0.675	0.681	0.0393	−0.0790	0.0656
2−sec	302	0.643	0.664***	0.0395*	−0.0555	0.0304**
HR deceleration	243	0.625	0.701***	0.0493***	−0.0860***	0.0589***
HR acceleration	216	0.518	0.555***	0.0367**	−0.0692**	0.0468
Prestim., Immed.,	532	0.704	0.710*	0.0339	−0.0551	0.0402
2-sec, HR dec.	545	0.642	0.686***	0.0410***	−0.0580***	0.0315***

†Significance test for R^2 represents a significant improvement in R^2 for the model estimated with the empirical data relative to the model based on the b-weights from the prestimulus saccades. Significance tests for the polynomial terms represent the significance of a Wald test for estimating the b-weights on the empirical data, relative to using the b-weights from the prestimulus saccades. The b-weights of all three polynomial terms contribute significantly to the regression equation.
*$P < 0.05$; **$P < 0.01$; ***$P < 0.001$.

velocity (radians × 10⁻² sec) and total amplitude (radians) of the saccades was examined with polynomial regression (maximum velocity = b_{linear} × amplitude + $b_{quadratic}$ × amplitude^2 + b_{cubic} × amplitude^3 + $b_{quartic}$ × amplitude^4 + ...). The multiple regression coefficient was significant for the linear relation alone (R^2 = 0.6095, b = 0.01466, N = 2119, $F(1,2117)$ = 3303.8, $P < 0.0001$). Adding the quadratic and cubic terms to the equation significantly improved the regression equation (R^2 difference = 0.0553, $F(2,2116)$ = 181.8, $P < 0.0001$). Adding polynomial terms beyond the cubic term was not statistically significant (e.g., quartic term, P = 0.4125). Figure 2(A) shows the scatterplot for the maximum velocity/total degrees relation, and the predicted line for the polynomial regression equation. Table 3 has the coefficients for the polynomial terms in the regression equation.

Table 3 contains the b-weights and R^2 comparing the prestimulus saccade model with the models from the experimental conditions, and Fig. 2(B)-(D) show the scattergram for these comparisons. The b-weights of the regression model for the prestimulus saccades were not improved by estimating b-weights from the actual data for the blinking dot saccades [Table 3 and Fig. 2(B)], and the prestimulus and immediate peripheral stimulus saccades [Table 3 and Fig. 2(C)]. The heart rate acceleration condition had data that were poorly fitted by the b-weights from the prestimulus period [Table 3, Fig. 2(D)]. Two experimental conditions [2-sec, heart rate deceleration; Fig. 2(E)] had data that poorly fitted the b-weights from the prestimulus period, and had empirical b-weights fit the data better than the prestimulus b-weights (Table 3).

Because of the lack of fit between the 2-sec and heart rate deceleration conditions with the model developed on the prestimulus saccades, the data from those two

conditions were examined more closely. There was no difference between the model fit of the data from those two conditions, and the addition trials or replacement trials for those two conditions. The three ages in the 2-sec and the heart rate deceleration conditions did have main sequence relations that differ. Figure 2(F) shows the scattergram and best fitting third-order polynomial regression line for the 14, 20, and 26-week-old infants separately. It also contains the linear and third-order regression lines derived from the prestimulus saccades. The 14-week-old main sequence relation was similar to that from the prestimulus period. The fit estimate from the 14-week-olds for this condition was not significantly different from the prestimulus model. The 20 and 26-week-olds' velocity–amplitude relation shows a steeper slope with only the linear coefficient of the polynomial equation being significant. The maximum velocity of the saccades was faster for equivalent amplitude saccades for these two ages during these conditions relative to the 14 week old infants, or relative to the 20 and 26-week-old infants' velocity–amplitude relation in the prestimulus period. A similar analysis of the main sequence for the prestimulus, immediate, and heart rate acceleration experimental conditions found no difference between the testing ages in the fit of the saccades from these conditions with the saccades from the prestimulus period [e.g., Table 3; Fig. 2(C) or Fig. 2(D)].

Multiple saccades and head movements. The single/ multiple saccade localizations were examined in relation to head movements accompanying the localization. Head movement on a trial was significantly related to whether single or multiple saccades occurred, χ^2 (1, N = 819) = 29.06, $P < 0.0001$. Peripheral stimulus localization was achieved with a single saccade on 70.3% of the trials in which no head movement accompanied the localization. In contrast, the trials in which head move-

(a) Prestimulus period

## (b) Blinking dot

(c) Prestimulus, immediate
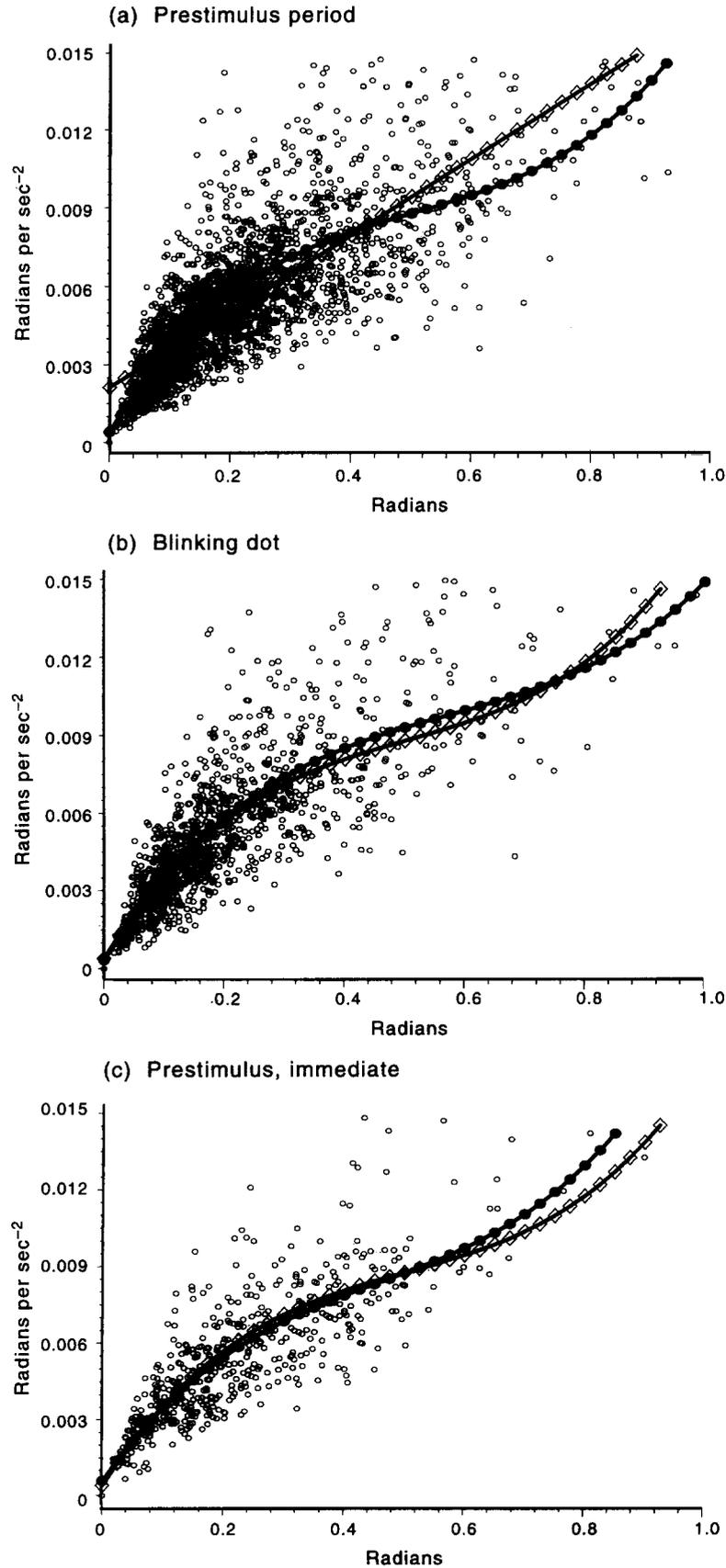
FIGURE 2. Main sequence relation between maximum saccade velocity and total amplitude of saccade, with the third-order polynomial regression line estimated from the prestimulus saccades and the best-fitting polynomial regression line. (A) Prestimulus saccades; (B) saccades toward blinking dot; (C) saccades to peripheral stimulus in prestimulus and immediate conditions; (D) saccades to peripheral stimulus in heart rate acceleration condition; (E) saccades to peripheral stimulus in 2-sec and heart rate deceleration conditons; (F) saccades to peripheral stimulus in 2-sec and heart rate deceleration conditions, with separate regression lines for 14, 20, and 26-week-old infants. Key: (A) <>, linear equation; °, linear + quadratic + cubic equation; (B)–(E) <>, prestimulus b-weights; °, estimated b-weights; (F) 1, 14-week-olds; 2, 20-week-olds; 3, 26-week-olds.

(d) Heart rate acceleration

**(e) 2–sec, heart rate deceleration**

(f) 2–sec, HR–Dec, by ages
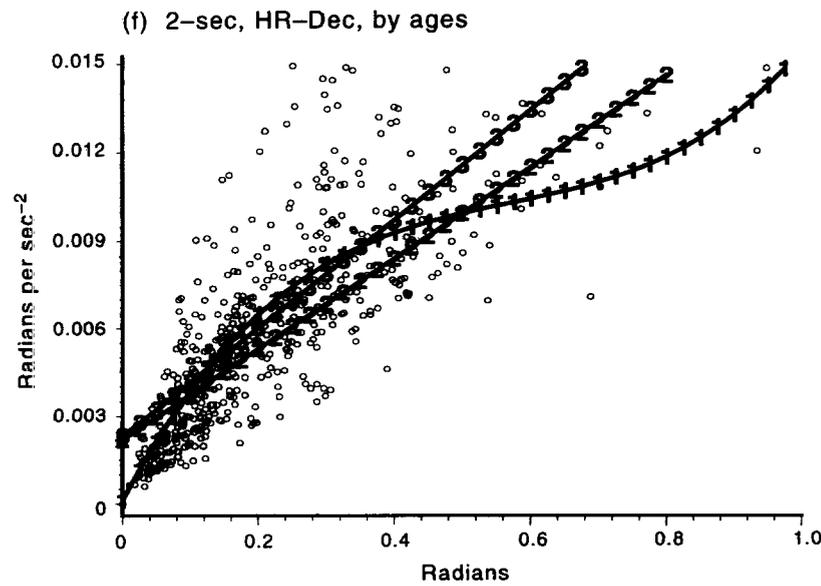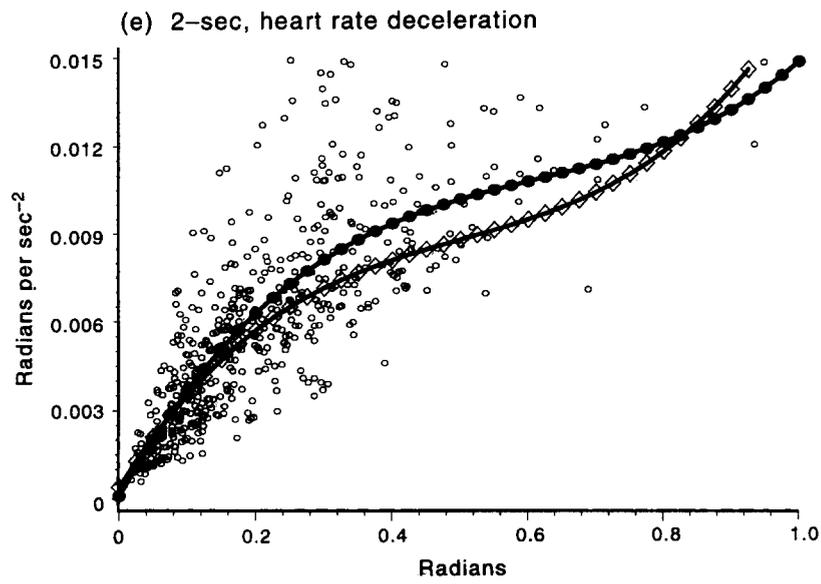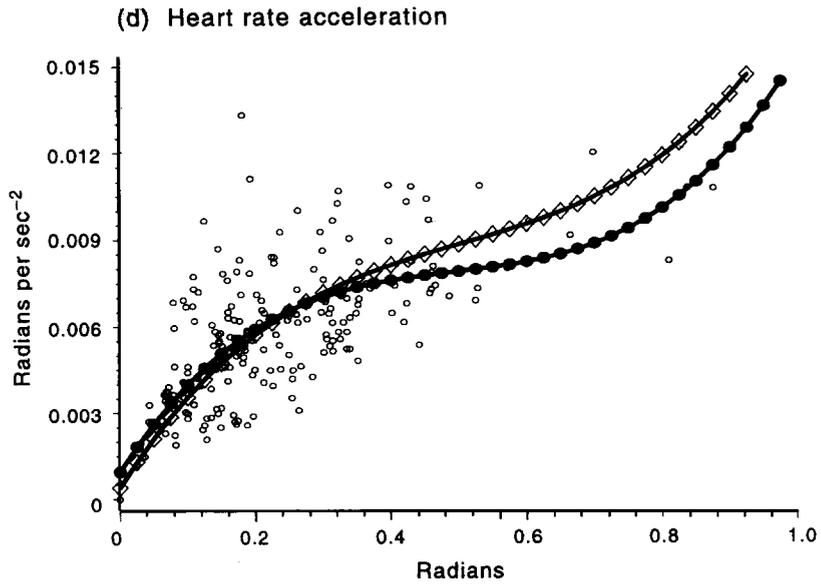
FIGURE 2(d–f). *Caption opposite.*

ment aided localization had approximately equal single/multiple saccades (48.5% single saccades). Age and head movement together also affected whether single or multiple saccades occurred, χ^2 (2, $N = 819$) = 5.77, $P = 0.0559$. The three ages localized the peripheral stimulus on the no head movement trials with single saccades with approximately equal frequency (percent single saccades, 14 weeks, 64.5%, $N = 93$; 20 weeks, 73.4%, $N = 79$; 26 weeks, 73.2%, $N = 97$). Multiple saccades decreased in frequency with increase in age on the trials in which head movements accompanied localization (percent single saccades, 14 weeks, 36.2%, $N = 196$; 20 weeks, 46.8%, $N = 188$; 26 weeks, 65.0%, $N = 166$), similar to the overall pattern (Table 2). The velocity–amplitude relation (main sequence) for the trials with and without head movements during the localization was examined. The main sequence relation on those two types of trials was similar and was not significantly different from that found in the saccades of the prestimulus period [e.g., Fig. 2(A)].

DISCUSSION

As has been reported in many studies, the presence of a competing stimulus in the focal visual field resulted in a lower localization percentage for a peripheral stimulus. This effect was due to attention engagement with the focal stimulus rather than due simply to the central stimulus' presence. Most localizations at these eccentricities were accompanied by head movements, and the probability, head movement amplitude, and EMG activity accompanying head movement, increased with increasing eccentricity of the peripheral stimulus. Several trials were identified where head movements toward the peripheral stimulus were made but fixation was maintained on the central stimulus, particularly among the older infants in the conditions in which attention was engaged. The stimuli were localized primarily with multiple saccades, the majority of which were localizing–corrective saccades. Step-like hypometric saccades made up only a small percentage of the multiple eye movements. Velocity–amplitude characteristics of the saccades ("main sequence") were similar between the prestimulus period and saccades made without a central stimulus or immediately upon presentation. Main sequence relations differed for the older two ages between the attentive conditions (2-sec and heart rate deceleration) and prestimulus saccades. The main sequence relation was substantially preserved on the trials on which head movements occurred.

An important finding of this study is that head movements play a large role in peripheral stimulus localization. The large proportion of localizations at these eccentricities (25–45 deg) was accomplished with saccadic eye movements and head movements. These findings agree with previously informally reported findings that head movements play an important role in stimulus localization for infants at these ages (Regal et al., 1983; Regal & Salapatek, 1982; Roucoux et al., 1982, 1983; Tronick & Clanton, 1971). The characteristics of the head

movement were related to the eccentricity of the peripheral stimulus. The probability and amplitude of the head movement were correlated positively with stimulus eccentricity, and the peak RMS activity and latency increased with eccentricity. Head movement amplitude was not linearly related to stimulus eccentricity. An inspection of the stimulus eccentricities and head movement size shows that the head movement amplitude covered nearly all of the smallest eccentricity (difference = 0.010 radians), but only part of the middle (difference = 0.104 radians) and largest (difference = 0.176 radians) eccentricities. The finding that the probability of head movements was related to eccentricity is consistent with adult research reporting that head movements occur infrequently to stimuli of target eccentricities of less than 20 deg, and more frequently to eccentricities of greater distance (e.g., Tomlinson & Bahra, 1986a, b).

There were two unusual characteristics of the head movements. First, on a large proportion of the trials (49%) the EMG activity and/or the video-judged head movement preceded saccadic onset. This pattern of head movement is found in adults primarily under "predictive" or "anticipatory" localizations, whereas under "visually guided" localizations, as in this study, EMG activity onset occurs concurrent with saccade onset, and head movement follows (e.g., Zangemeister & Stark, 1982). Second, a reasonably large proportion (38%) of the non-localization trials had head movements moving in the direction of the peripheral stimulus while fixation remained on the focal stimulus (e.g., EMG activity, video-judged head movement, and VOR compensatory EOG change). This type of head movement occurred mostly on the trials for which attention should be engaged, and more frequently in these attention conditions for the two oldest ages. Though both head and eye movements may be used for localization, these two findings are consistent with a model positing the relative independence of the systems controlling head movement and eye movement (e.g., Tweed et al., 1995).

The characteristics of the saccadic localization may be compared profitably with the Aslin & Salapatek (1975) study. First, the presence of multiple saccades to targets in this eccentricity decreases over the age range from 1 to 6 months. Aslin and Salapatek reported that the proportion of multiple saccades to stimuli at 20–40 deg decreases from 86 to 75% from 1- to 2 months of age. This study shows this decrease continues from 3- to 6 months of age (55, 45, 32% for 14, 20, and 26 week olds, respectively). Second, Aslin and Salapatek reported that the multiple saccades consisted of fixed amplitude hypometric saccades to localize the target. For 10 and 20 deg targets, approximately 60–70% of the multiple saccades differed by less than 20% (Aslin & Salapatek, 1975, Note 9). Thus, within a localizing saccadic eye movement the multiple saccades were hypometric and of fixed amplitude. These proportions differ greatly from those found in this study. Multiple hypometric saccades differing in amplitude by less than 20% were a much

smaller proportion (21%) of the multiple saccades. Rather, as has been reported for multiple saccades in adult subjects (Becker, 1976; Prablanc & Jennerod, 1975; Prablanc et al., 1978), a large saccade traversed the majority of the distance to the peripheral target, and was followed by a small "corrective" saccade for final target localization.

There are several differences between the Aslin & Salapatek (1975) study and this study that may account for this difference in the proportion of fixed amplitude hypometric saccades. This study analyzed saccades from 25 to 45 deg, whereas Aslin and Salapatek only reported on the fixed amplitude hypometric saccades for 10 and 20 deg. A large proportion of the trials in the current study included head movements, which may have affected the type of saccade. The infants in the Aslin and Salapatek study had head movements restrained. The infants in this study were sitting, whereas the infants in the Aslin and Salapatek were supine. The possibility that the different age groups used in the two studies contributes to the difference does not seem likely. The proportion of multiple eye movements shows a gradual decline between the 2- and 3-month-old subjects (75% to 55%) whereas the difference in proportion of multiple saccades is much larger (>60% for both ages combined in Aslin and Salapatek, compared with 25% for the 14-week-olds in this study). Other studies using infants in the same age range as that used by Aslin and Salapatek did not show this pattern of fixed amplitude hypometric saccades (Hainline et al., 1984; Hainline & Abramov, 1985). Thus, age per se does not account for this difference. There have been no other studies of these types of peripheral localizing saccades in the age range and at the eccentricities used by Aslin and Salapatek that report the fine detailed analysis they did.

Perhaps the most interesting aspect of the saccadic localizations was the effect of the attention conditions on the peak velocity–amplitude relation ("main sequence"). There was a strong relation between peak velocity and amplitude of the localizing saccades during the "pre-stimulus" period with a simple non-patterned stimulus array [Fig. 2(A)]. The regression equation relating peak velocity and amplitude was similar to that found for the saccades to the blinking dot, and localizing saccades in the prestimulus peripheral stimulus condition and immediate peripheral stimulus condition [Fig. 2(B, C) and Table 3]. There were no age changes in this main sequence relation, and it is assumed that adult-like relations characterize these velocity/amplitude relations. In contrast, in the two conditions under which focal stimulus attention is maximally engaged (2-sec and heart rate deceleration) unusual velocity/amplitude relations were found. This consisted of a faster peak velocity relative to saccade amplitude than during prestimulus periods. This effect occurred primarily in the 20 and 26-week-old infants [Fig. 2(F)]. These age differences were not found in any other condition, nor in the prestimulus period or the saccades to the blinking dot. Hainline et al. (1984) reported a contrasting result. They found that the

main sequence in the "attentive" condition was more similar to adult relations than the infant main sequence in the "inattentive" condition. However, they were studying saccades while infants scanned foveal stimulus scenes, so that attention invigorated the eye movement system. In the current study the effects of attention are to inhibit localization and reflexive eye movements towards the peripheral stimuli.

The neural systems that control localizing head and eye movements may be relevant for understanding these results. The characteristics of the main sequence are probably due to burst cells located in the brainstem regions (Moschovakis & Highstein, 1994), which are controlled by the topographic amplitude–eccentricity map of the superior colliculus (SC) (Peck, 1984, 1987; Sparks & Groh, 1995; Wurtz & Munoz, 1995). The SC motor map at small eccentricities involves only eye movements, but at larger eccentricities causes both eye and head movements to localize the peripheral stimulus (Cowie & Robinson, 1994; Cowie et al., 1994; Freedman et al., 1993; Peck, 1990). At even larger eccentricities, outside the "oculomotor range" (Guitton, 1991, 1992), head movements play an increasingly important role in traversing the eccentricities necessary for localizing movements. A recent study found that stimulation of the SC produced eye movements alone, eye–head movements, and head movements alone (Cowie & Robinson, 1994; Cowie et al., 1994). The eye and head movements had onset latency, durations, and sizes that were not well correlated (also see Tweed et al., 1995). These findings suggest that the control of head and eye movements for visually guided ("reflexive") peripheral stimulus localization are partially independent (cf., "gaze shift feedback" hypothesis, Guitton, 1991, 1992; Guitton et al., 1990). This independence is reflected in the present study in the attention-related head movements that occur without localizing eye movements and the relative independence of the main sequence relation to head movements.

The interpretation of the effect of attention on the main sequence, and on peripheral stimulus localization generally, involves an understanding of the brain systems controlling eye movement during attention. A brain system involving the parvocellular pathway from the retina through lateral geniculate nucleus, primary and secondary visual areas, parietal cortex, and frontal eye fields controls targeted eye movements during attention (Hood & Atkinson, 1993; Johnson, 1990, 1995; Richards & Hunter, 1998; Schiller, 1985, Schiller, 1998). This "posterior attention network" (Posner, 1995; Posner & Petersen, 1990) inhibits the reflexive saccades primarily controlled by an eye movement system involving the magnocellular cells from the retina through the primary visual area, suprasylvian cortex and superior colliculus. Recent work has suggested that the focal stimulus attention in infants' changes, attenuates response processes such that a response is less likely during attention to the central stimulus than during inattention, or without a central stimulus (Hicks & Richards, 1996; Richards,

1997). The heart rate changes during attention probably index a general arousal/alertness system (Heilman et al., 1987; Mesulam, 1983; Posner, 1995; Robbins & Everitt, 1995) that "invigorates" the posterior attention network (Richards & Casey, 1992). The saccades that manage to avoid this inhibition may be unusual. Perhaps saccade amplitude is programmed and then attention-based inhibitory systems affect saccade parameters (e.g., pre-emptive shutdown of burst neurons leading to shorter-than-usual amplitude for a given velocity). The changes in the main sequence relation for the attention conditions in the two older ages groups, and the unusual head movements toward the peripheral stimulus in the absence of localizing saccades, reflect the inhibition of the reflexive system by the attention system. These results are consistent with a "neuro-developmental" model hypothesizing a focal attention system that over this age range increasingly inhibits reflexive saccadic eye movements used to localize peripheral stimuli (Johnson, 1990, 1995; Richards & Casey, 1992; Richards & Hunter, 1998).

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