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Infant Attention and the Development of Smooth Pursuit Tracking

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The effect of attention on smooth pursuit and saccadic tracking was studied in infants at 8, 14, 20, and 26 weeks of age. A small rectangle was presented moving in a sinusoidal pattern in either the horizontal or vertical direction. Attention level was distinguished with a recording of heart rate. There was an increase across age in overall tracking, the gain of the smooth pursuit eye movements, and an increase in the amplitude of compensatory saccades at faster tracking speeds. One age change was an increase in the preservation of smooth pursuit tracking ability as stimulus speed increased. A second change was the increasing tendency during attentive tracking to shift from smooth pursuit to saccadic tracking when the stimulus speed increased to the highest velocities. This study shows that the development of smooth pursuit and targeted saccadic eye movements is closely related to the development of sustained attention in this age range.

Human infants are born with an immature visual system. A number of visual abilities seen in adults are not available to the human newborn but emerge during the first few months of life. One ability that emerges in the first six months is the tracking of visual stimuli, particularly tracking with smooth pursuit eye movements. At birth and up to 1 month of age, tracking of visual stimuli is relatively poor, it occurs only at relatively slow stimulus speeds, and it generally involves saccadic eye movements rather than smooth pursuit eye movements (Aslin, 1981; Dayton & Jones, 1964; Dayton, Jones, Steele, & Rose, 1964; Hainline, 1988; Kremenitzer, Vaughan, Kurtzberg, & Dowling, 1979; Phillips, Finocchio, Ong, & Fuchs, 1997). Between 4 and 8 weeks of age, smooth pursuit eye movements seem to be more easily elicited over a wider range of stimulus characteristics and target speeds, though smooth pursuit tracking is often interspersed with saccadic tracking, and the eye movement characteristics of smooth pursuit are still not at adult levels (e.g., Aslin, 1981; Phillips et al., 1997; Roucoux, Culee, & Roucoux, 1983). Between 2 and 6 months of age there appears to be a rapid development in smooth pursuit target tracking (Aslin, 1981; von Hofsten & Rosander, 1996, 1997). This study assessed the development of smooth pursuit and saccadic tracking in infants from 2 to 6 months of age and the effect that attention has on the development of tracking during this age period.

There are two major changes in tracking eye movements in the first six months. One change is the speed of the target for which smooth pursuit tracking will occur. At least two studies have found what appear to be smooth pursuit eye movements in neonates, but only at very slow target speeds (a range of 4 to 9 deg/s) and only for very large targets (6° to 16°; Dayton & Jones, 1964; Hainline, 1988; Kremenitzer et al., 1979). Studies of infants younger than 8 weeks of age report that smooth pursuit eye movements will occur to targets moving less than about 10 deg/s (Phillips et al., 1997; Roucoux et al., 1983), but to targets greater than 10 deg/s tracking at this age is primarily saccadic (Aslin, 1981; Roucoux et al., 1983). Between 2 and 6 months of age the speed at which tracking occurs reaches adult levels (Aslin, 1981; von Hofsten & Rosander, 1997).

A second change in tracking eye movements is the ability of infants to use smooth pursuit eye movements at faster tracking speeds for a larger proportion of their tracking. Stimulus tracking before 6 weeks of age to stimulus speeds greater than about 9 deg/s is primarily saccadic (Aslin, 1981; Roucoux et al., 1983), though smooth pursuit tracking occasionally occurs for much slower target speeds (Hainline, 1988; Kremenitzer et al., 1979). From 6 weeks of age until about 6 months of age, the speed at which targets are pursued with smooth pursuit eye movements gradually increases (Aslin, 1981; Phillips et al., 1997; von Hofsten & Rosander, 1997). At the beginning of this period (e.g., 2 months), the tracking of smoothly moving objects (e.g., sinusoidal or triangular motions; von Hofsten & Rosander, 1997) consists of smooth pursuit eye movements that are interspersed with saccadic eye movements. The proportion of tracking that is accomplished by smooth pursuit eye movements increases over this age range such that at increasingly faster speeds there is a higher proportion of tracking accomplished by smooth pursuit eye movements.

A recent study by von Hofsten and Rosander (1997) illustrates the change in the use of saccadic and smooth pursuit eye movements in stimulus tracking. They had infants at ages 9, 15, and 21 weeks (approximately 2, 3, 5 months) track a 10° face stimulus at tracking speeds of 10, 20, and 40 deg/s. They studied overall "gaze" tracking, which includes both smooth pursuit and saccadic tracking, and separated gaze tracking into smooth pursuit and saccadic tracking. They found that gaze tracking gain in 2-month-olds was accomplished primarily by smooth pursuit eye movements for slow stimuli (10 deg/s) and this changed little from 2 to

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5 months of age (e.g., percentage of gain attributed to smooth pursuit tracking was 80%, 85%, 87% for 9-, 15-, 21-week-old infants). Gaze tracking gain for faster stimuli (20 deg/s) had more saccadic eye movements at 2 months (approximately 65% attributed to smooth pursuit tracking), but by 3–4 months gaze tracking gain was similar to the slower tracking speed (approximately 80% attributable to smooth pursuit eye movements). Finally, at very fast tracking speeds (40 deg/s) the majority of gaze tracking gain was attributable to saccadic eye movements at 2 months of age (approximately 45% attributable to smooth pursuit eye movements), and the amount of smooth pursuit eye movements increased dramatically over this age period (approximately 45%, 65%, 70% for 9-, 15-, 21-week-old infants). The developmental change in eye movements thus includes the ability to track faster moving stimuli and also influences whether saccadic or smooth pursuit eye movements will be used as stimulus speed increases.

Infant attentiveness has been suggested as a mediating factor in the development of tracking eye movements, though this has not been systematically investigated. Several investigators have suggested that failures to find smooth pursuit tracking in very young infants may be due to the failure of small, simple stimuli, moving at oscillating frequencies, to elicit attentiveness in the infant (Hainline, 1988; Roucoux et al., 1983; Shea & Aslin, 1990). Interesting targets such as faces (von Hofsten & Rosander, 1996, 1997), a "Mickey Mouse" face (Roucoux et al., 1983), or circles, bullseyes, or faces (Hainline, 1988; Kremenitzer et al., 1979) may elicit smooth pursuit eye movements in infants 8 weeks of age or younger, whereas simple rectangle targets do not (Aslin, 1981). Alternatively, Shea and Aslin (1990), using a simple target in a nonpredictable path, found smooth pursuit eye movements in younger infants. They argued that the nonpredictable target paths were more likely to elicit attention than oscillating target paths for infants below 8 weeks of age. However, attention level was not systematically varied in these studies, and several stimulus factors differ across the studies finding smooth pursuit eye movements at the earliest ages (e.g., stimulus size, or target path). This study is the first to systematically measure attention level during stimulus tracking in young infants to determine how attention affects eye movement characteristics during stimulus tracking.

This study had two goals. The first was to do a systematic, quantitative study of smooth pursuit and saccadic eye movements in infants from the age of 2–6 months. Infants at 8, 14, 20, and 26 weeks of age were presented with a small target that moved in either a horizontal or vertical sinusoidal pattern. The target was presented at five different velocities (from 4 to 24 deg/s) to establish the accuracy of target tracking at different speeds. The electrooculogram (EOG) was used to measure the eye movements. The eye movements were analyzed as overall tracking containing both smooth pursuit and saccadic components, and also were separated into saccadic and smooth pursuit components. We expected that the primary developmental change across this age range would be a preservation of tracking ability across a wider range of stimulus speeds.

The second goal of this study was to examine the influence of attention on eye movements during tracking in infants. We used heart rate (HR) changes during the tracking of the stimulus as a measure of attention. Heart rate changes in infants can be used to distinguish between periods of time before attention is fully engaged, when active and sustained attention is occurring, and when attention is disengaged though fixation continues (Lansink, Mintz, & Richards, 1998; Lansink & Richards, 1997; Richards & Hunter, 1997, 1998). Thus, we defined "stimulus orienting" (or "look onset") as the period of time when fixation was directed toward the moving tracking stimulus but before HR deceleration occurred. "Sustained attention" (or "sustained heart rate deceleration") was defined as a period of time after HR decelerated and a sustained lowered HR was maintained. "Attention termination" (or "return of heart rate to prestimulus level") was defined as the period of time after HR had decelerated and then had returned to its prestimulus level, while the infant continued looking at the tracking stimulus. Recent models of the neural systems controlling infant eye movement development (Johnson, 1995; Johnson, Gilmore, & Csibra, 1998; Richards & Casey, 1992; Richards & Hunter, 1998) hypothesize that there are developmental changes in attention over this age range that enhance neural areas responsible for stimulus tracking during attention. It was hypothesized that the development of attention over this age range would be reflected in age-related changes in pursuit tracking during sustained attention to a much greater degree than stimulus orienting or attention termination. We also hypothesized that "attention-directed/targeted saccades" would show an increase over this age range, and that saccadic tracking during periods of relative inattentiveness would show little age change from 2 to 6 months of age.

Method

Participants

Infants were recruited from birth notices published in a Columbia, South Carolina, newspaper. The infants were full term, defined as having birth weight greater than 2,500 g, and gestational age of 38 weeks or greater based on the mother's report of her last menstrual cycle. A cross-sectional design was used to sample 10 infants in each of four age groups: 8, 14, 20, and 26 weeks of age. The ages of the infants at testing were 8 weeks (M = 56.9 days, SD = 3.07, 7 male, 3 female), 14 weeks (M = 101.9 days, SD = 4.33, 4 male, 6 female), 20 weeks (M = 140.7 days, SD = 4.94, 5 male, 5 female), and 26 weeks (M = 187.7 days, SD = 4.24, 6 male, 4 female). Ten additional participants were tested who became fussy or sleepy during the testing session, or who did not complete enough trials to be included in the analyses. The infants had no acute or chronic pre- or perinatal medical complications and were in good health at the time of recording. The infants had no obvious signs of strabismus and were not under pediatric or opthamologic care for visual difficulties.

Apparatus and Stimuli

The infant was held on the parent's lap approximately 22 in. (55 cm) from the center of a black and white 19-in. (49-cm) television monitor. The TV monitor subtended a 44° horizontal visual angle and 33° vertical visual angle. The area around the TV monitor was covered with a light brown cloth to prevent the intrusion of extraneous visual information. A video camera was located above the TV monitor (approximately 19° above center). An observer judged infant fixations on a TV monitor in an adjacent room. The session was recorded on videotape with a time code to synchronize physiological and experimental information for analysis.

The visual stimuli consisted of presentations of a 2° wide × 6° high flashing rectangle that changed black–white intensity every 30 ms in a sinusoidal pattern. This rectangle moved at one of five average speeds in the horizontal or vertical direction for the duration of a trial: 4, 9, 14, 19, or 24 deg/s. The horizontal tracking stimulus consisted of the rectangle moving in the horizontal dimension with sinusoidal velocity at one of the five average speeds across the entire TV monitor width (44°), and with a constant linear vertical speed. The vertical tracking stimulus consisted of the rectangle moving in the vertical dimension with sinusoidal velocity at one of the five average speeds up and down the TV monitor height (33°), and with a constant linear horizontal speed. The horizontal tracking stimulus therefore appeared to be a sine wave located along the vertical axis, whereas the vertical tracking stimulus appeared to be a sine wave located along the horizontal axis. When the tracking stimulus reached an edge of the screen, it reversed direction. During each trial, after 10 to 20 s of stimulus movement (randomly chosen stimulus movement times between 10 and 20 s), the stimulus was paused and remained in that position until the observer judged that the infant was looking at the stimulus for 5 s. These pauses were used to allow the infants to locate the stimulus if they had not been tracking it and to calibrate eye movement measures. The position of the stimulus on the screen was recorded each millisecond to compute measures of stimulus–eye movement coherence and gain.

Procedure

The parent sat in a chair in the viewing area with the infant on the parent's lap facing the TV monitor. Each trial began with the presentation of the tracking stimulus on the monitor. When the observer judged that the infant was looking toward the TV monitor, the tracking stimulus was presented and remained stationary for 2.5 s and then began moving. The observer judged the infant's fixation throughout the trial. The stimulus was paused at random intervals between 10 to 20 s if the infant was tracking it, or when the infant looked away from the TV screen. The stimulus remained paused until the observer judged that the infant was looking at the stimulus for 5 s. Each trial including stimulus movement time and pauses was 50 s in length, and condition representing stimulus speed and direction remained consistent throughout a trial. At the end of each trial the screen went blank for a minimum of 7.5 s.

There were two within-subjects factors in the experiment: stimulus speed and stimulus direction. Each infant received trials with horizontal and vertical tracking stimuli at each of the five stimulus speeds (minimum 10 trials per participant). These conditions were presented randomly without replacement in 10-trial blocks. Each infant received a minimum of 1 of the 10 trial types and a maximum of 2 of each trial type. At the beginning of the presentation and after every three trials, a recording of a *Sesame Street* movie (*Follow That Bird,* without sound) was shown on the TV monitor for 10 to 15 s. These presentations were done to give the infant a break from the testing and were used to adjust the recording of the physiological measures. These presentations also were presented if the physiological recording needed adjustment.

Measurement and Quantification of Eye Movement

The EOG was used to measure eye movements. The EOG was recorded with 6-mm Ag-AgCl electrodes placed posterior to the external canthus of each eye and above and below the right eye. The connection between the EOG electrodes and the amplifier electrode box was 1 m, and the electrode box to the amplifier connection was actively shielded so that preamplification of the EOG signal was unnecessary. The EOG was digitized on-line at 1000 Hz (1 ms). The EOG was amplified at 2K and a DC-recording was made. Horizontal eye movements for the horizontal tracking stimulus (sinusoidal movement in the horizontal orientation) used the EOG recorded from the electrodes on the external canthi, whereas vertical eye movements for the vertical tracking stimulus (sinusoidal movement in the vertical orientation) used the EOG recorded from the electrodes above and below the right eye.

Overall tracking of the stimulus, the smooth pursuit component of tracking, and saccades during the stimulus were quantified from the EOG record. Overall tracking of the stimulus was defined as the composite EOG signal, which consists of both smooth pursuit and saccadic tracking. Smooth pursuit tracking and saccadic eye movements were quantified by separating the smooth pursuit component of the composite EOG signal (smooth pursuit tracking) from the saccadic component of the composite EOG signal. The saccades were separated from the composite EOG record with an algorithm presented in Matsuoka and Ueda's work (1986; Matsuoka & Harato, 1983). The use of a simple velocity threshold does not adequately distinguish saccades from pursuit eye movements, whereas the acceleration of saccades is much greater than that of smooth pursuit eye movements. The Matsuoka and Ueda algorithm uses a third-order differential equation, sensitive to sudden changes in acceleration, to identify saccades. The composite EOG signal was filtered with this equation and saccades were identified using a threshold on the filtered data that indicated a saccade had occurred. A computer-based editing program was used to confirm with visual judgment the algorithm identification of each saccade, and the onset and offset of the saccade were calculated. 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 ending points of the saccade. Finally, the difference between the interpolated smooth pursuit signal and the composite signal was the resultant saccadic component. Saccades were quantified throughout the trials. We computed the onset/offset of the saccade, the maximum velocity of the saccade during its occurrence, and the EOG amplitude (μV) at the beginning and end of the saccade.

The three eye movement types were calibrated by using the fixation on the signal when it was stationary 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, Preston, & Fuchs, 1990; Richards & Hunter, 1997; Woestenburg, Verbaten, & Slangen, 1984). The fixation points were the times during the trial when the tracking stimulus was stationary and the observer judged that the infant was looking at the stimulus. The difference in degree and difference in EOG values for fixation on successive pauses within a trial were calculated. 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 when the head does not move. Thus, we eliminated successive pauses that contained a head movement between pauses. 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, Hainline, & Abramov, 1981; Richards & Hunter, 1997; Woestenburg et al., 1984). The three eye movement types were adjusted by the *b* weight, so that comparisons between the tracking stimulus and the eye movements could be made directly. Given the confirmation of saccade identification with visual judgments (previous paragraph) and some inherent instability of the calibration procedure (e.g., about 2°; see Richards & Hunter, 1997), we believe that saccades down to about 2° to 3° were identified.

Interbeat Interval Changes and Heart Rate Phases

The electrocardiogram (ECG) was recorded during the entire session. The ECG was recorded with Ag-AgCl electrodes placed on the infant's chest using disposable electrode collars. The ECG was digitized at 1000 Hz (each ms). The R-wave was identified in the ECG, and the interbeat interval (IBI) was defined as the duration between successive R-waves in the ECG. Artifact correction was done using the Cheung (1981) and Berntson, Quigley, Jang, and Boysen (1990) algorithms along with a visual inspection of the beats.

The IBI changes were used as a physiological measure of attention (Lansink & Richards, 1997; Lansink et al., 1998; Richards & Hunter, 1997, 1998). The IBI changes and fixation judgments were used to define three periods thought to differ in attention engagement: look onset (stimulus orienting), sustained HR deceleration (sustained attention), and return of HR to prestimulus level (inattentive fixation). These periods were defined according to significant HR changes occurring at the onset of a look and continuing throughout a look. Look onset was defined as any period at the beginning of a look that preceded the beginning of the deceleration of HR. Sustained HR deceleration was defined as beginning with the onset of a deceleration in HR, defined as five successive beats with heart period longer than the median period of the five prestimulus beats. The return of HR to prestimulus level was defined as five successive beats with heart period shorter than the median period of the five prestimulus (or prelook) beats, and must have followed a deceleration. Following Lansink et al. (1998), we defined the HR deceleration period as beginning with the first beat that met the criterion until the first beat that began the return of HR to its prestimulus level.

Fixation Judgments

A single observer judged the infant's fixation direction during the experiment in an adjacent room on a TV monitor to control the experimental protocol. Each session was judged off-line. A time code recorded on the videotapes allowed the judgment to have millisecond accuracy, though resolution was limited to a single video frame scan (1/2 total frame length = ~16 ms). The time code on the videotape was synchronized with the computer clock to synchronize the judgments with the experimental events and physiological recordings. The observer judged the infant to be looking at the stimulus, looking away from the stimulus, or making a head movement. The quantification of eye movements was made only for periods where the observer judged that the infant was looking in the direction of the stimulus. The judgments also were used in the calibration procedure to ensure that no head movements were made between successive pauses of the stimulus. We have found in previous studies (e.g., Hicks & Richards, 1998; Richards & Hunter, 1997) that observers' judgments of infants' looking at stimuli result in interobserver agreement greater than 94%, and so did not use a second observer to check for reliability of observer judgments in this study. Thus, looking at the stimulus during the pauses should be reliably and accurately judged, whereas observers' judgments about looking during tracking stimulus movement could only ensure the infant was looking in the general direction of the stimulus.

Experimental Design for Statistical Analysis

The experimental factors for the statistical analyses included the between-subjects factors of testing age (4: 8, 14, 20, 26 weeks) and within-subject factors of stimulus speed (5: 4, 9, 14, 19, 25 deg/s) and tracking direction (2: horizontal, vertical). Some of the analyses included an attention phase factor (3: look onset, sustained HR deceleration, return of HR to prestimulus level). The analysis was done with analysis of variance.[1] One dependent variable was the amount of tracking time. The other dependent variables were obtained from the three eye movement types. Coherence and gain were calculated for overall stimulus tracking and smooth pursuit tracking, and number of saccades was calculated for the saccadic tracking. In any look the value for these variables was calculated over the entire look, and the value for these variables also was apportioned into the attention phase categories (look onset, sustained HR deceleration, return of HR to prestimulus level) depending on the proportion of time the look overlapped these attention phases. The eye movement variables were calculated only from the time when the stimulus was moving and represent tracking of the moving stimulus.

Spectral and cross-spectral analyses were done to estimate tracking coherence and gain. Spectral analyses were done on the recorded position of the tracking stimulus, overall stimulus tracking (composite EOG signal), and smooth pursuit tracking (smooth pursuit component of the composite EOG signal). Cross-spectral analyses were done between the recorded position of the tracking stimulus during its movement and each of the two eye movement signals. Coherence between the tracking stimulus and the eye movements was defined based on the ratio of the cross-spectral power between measures and the product of the spectral power of each measure. The coherence was calculated separately for the stimulus and overall stimulus tracking and for the stimulus and smooth pursuit tracking. The coherence is an estimate of how well the frequency of the tracking stimulus was duplicated by the frequency of the eye movements. Gain was defined as the ratio of the power spectrum of the eye movement type (overall stimulus tracking, smooth pursuit tracking) to the power spectrum of the tracking stimulus movement. The gain is an estimate of how well the amplitude of the tracking stimulus was duplicated by the amplitude of the eye movements. Gain was calculated only for looks where the coherence between the tracking stimulus and the composite EOG was greater than .40. This ensured that the gain was calculated only when the infant was tracking the stimulus.[2]

Results

Tracking Time

The time spent tracking the stimulus for the 50 s of the trial was first examined. As expected, there was a main effect of testing age on tracking time, $F(3, 36) = 5.92, p = .0022$. Figure 1 shows the time spent looking toward the tracking stimulus and the percentage of the time spent looking for the attention phases. The 8- and 14-week-old infants spent more time looking toward the tracking stimulus than did the 20-week-old infants or the 26-week-old infants. The infants at the youngest ages looked at the tracking stimuli for long periods of time, whereas the older infants alternatively looked toward the TV monitor and away from it, reducing total tracking time. This was not due to differences in attention per se. The proportion of looking time spent in inattentive fixation (e.g., when HR had returned to its prestimulus level but fixation continued) was higher for the two youngest ages than the two older ages. The youngest aged infants continued looking at the TV monitor for longer periods of time when inattentive. The two older age groups looked away from the stimulus more quickly, and thus had a higher proportion of accumulated time in the look onset (stimulus orienting) phase than did the two youngest age groups. Thus, the periods representing attentive fixation (stimulus orienting, sustained attention) occupied a larger proportion of looking time in the 20- and 26-week-old infants than in the 8- and 14-week-old infants. There were no statistically significant effects of stimulus speed or tracking direction on looking time.

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[1] The analyses of variance were done with a general linear models approach using nonorthogonal design because of the unequal distribution of trials and looks within a trial across factors, because of the different epoch numbers for the attention categories, and because all participants did not have all of the attention categories for each combination of stimulus movement conditions (Hocking, 1985; Searle, 1971, 1987). 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 (e.g., stimulus speed, stimulus direction, attention phase) within this class variable. The PROC GLM of SAS (1996) was used for the computations.

[2] The analyses also were done including all data and data with coherence > .20. These other analyses found a similar pattern of results (tracking speed, attention effects, etc.). We chose .40 as the minimum coherence for gain calculations because several of the coherence effects seemed to show a "floor effect" of .40 (e.g., Figure 2). We also decided that a minimum level of stimulus–eye movement coherence would ensure that tracking was actually occurring when the observer judged that the infant was gazing at the moving stimulus.

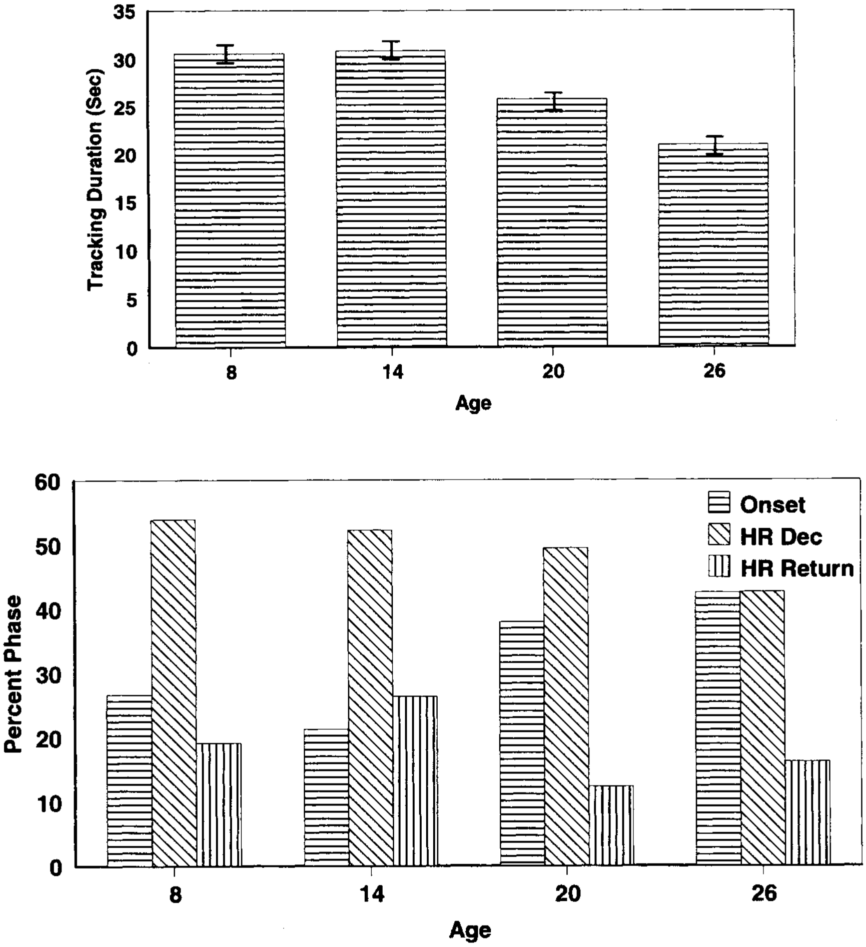

Figure 1. Stimulus tracking times as a function of age and percentage of time spent in the heart rate (HR)-defined attention phases. Dec = deceleration.

The 8- and 14-week-old infants spent more time looking toward the tracking stimulus, *M*s = 30.63 s (9.82) and 30.90 s (8.58), respectively, than did the 20-week-old infants, *M* = 25.83 (10.81), or the 26-week-old infants, *M* = 21.11 (11.11). The proportion of looking time spent in inattentive fixation (e.g., when HR had returned to its prestimulus level but fixation continued) was higher for the two youngest ages (23%) than the two older ages (15%). The youngest aged infants continued looking at the TV monitor for longer periods of time when inattentive, whereas the two older age groups looked away from the stimulus more quickly, and thus had a higher proportion of accumulated time in the look onset (stimulus orienting) phase (40%) then did the two youngest age groups (25%).

Stimulus–Eye Movement Coherence

The coherence between the frequency of the stimulus and the eye movements was analyzed. The coherence was calculated from the cross-spectral and spectral analysis of the stimulus and the two eye movements. The coherence represents how well the two frequencies match independent of actual eye position (e.g., gain or phase).

Overall stimulus tracking (composite EOG). The coherence between the composite EOG signal and the tracking stimulus represents the overall tracking of the stimulus (i.e., gaze, consisting of both smooth pursuit and saccadic eye movements). Figure 2 shows the coherence for overall stimulus tracking in the total trial as a function of stimulus speed for the vertical and horizontal eye movements.[3] Figure 2 also shows the gain for the overall stimulus tracking. Figure 3 shows the coherence for overall stimulus tracking for the HR-defined sustained attention and the return of HR to prestimulus level, separately for horizontal and vertical eye movements and for the testing ages (8 and 14 weeks combined, 20 and 26 weeks combined).

There were two statistically reliable findings for the overall stimulus tracking. First, there was a decrease in overall tracking with increases in stimulus speed. This is shown by the decrease in

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[3] More detailed figures are available showing the coherence and gain for overall stimulus tracking and smooth pursuit tracking function of stimulus speed, vertical and horizontal eye movements, separately for the four testing ages, and for the values apportioned by the HR-defined attention phases. See http://jerlab.psych.sc.edu.

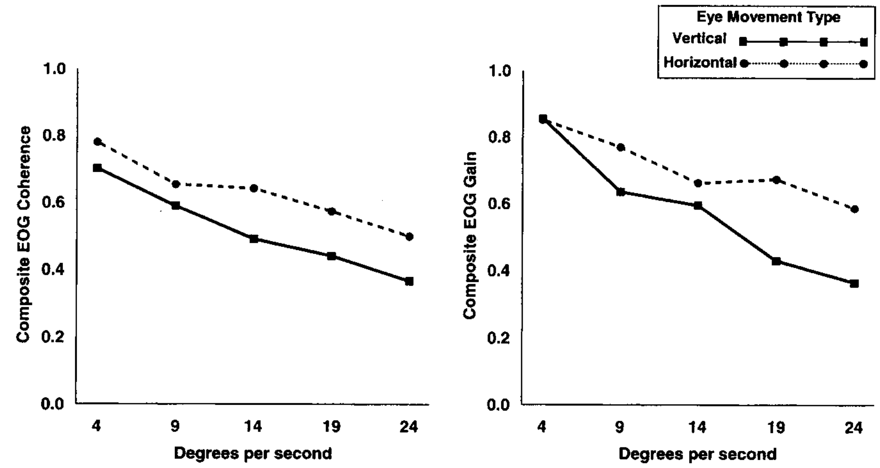

Figure 2. The coherence between the composite electrooculogram (EOG) signal and the tracking stimulus movement and gain of the composite EOG signal over the tracking stimulus, as a function of stimulus tracking speed, separated by vertical and horizontal eye movements.

coherence between the composite EOG signal and the tracking with increases in stimulus speed, $F(4, 135) = 20.53$, $p < .0001$. This effect of speed on overall stimulus tracking was true for both horizontal and vertical tracking stimuli and for tracking during the different attention phases (Figure 2). Second, there were differences across age in this effect of speed on overall stimulus tracking, $F(12, 135) = 2.55$, $p = .0045$. This difference in age for the effect of speed occurred primarily during the sustained HR deceleration periods of the trial (Figure 3). For the horizontal tracking stimulus, the two oldest ages showed less of an effect of speed on overall tracking during this attentive phase. The two older ages were better at stimulus tracking than the two younger ages, par-

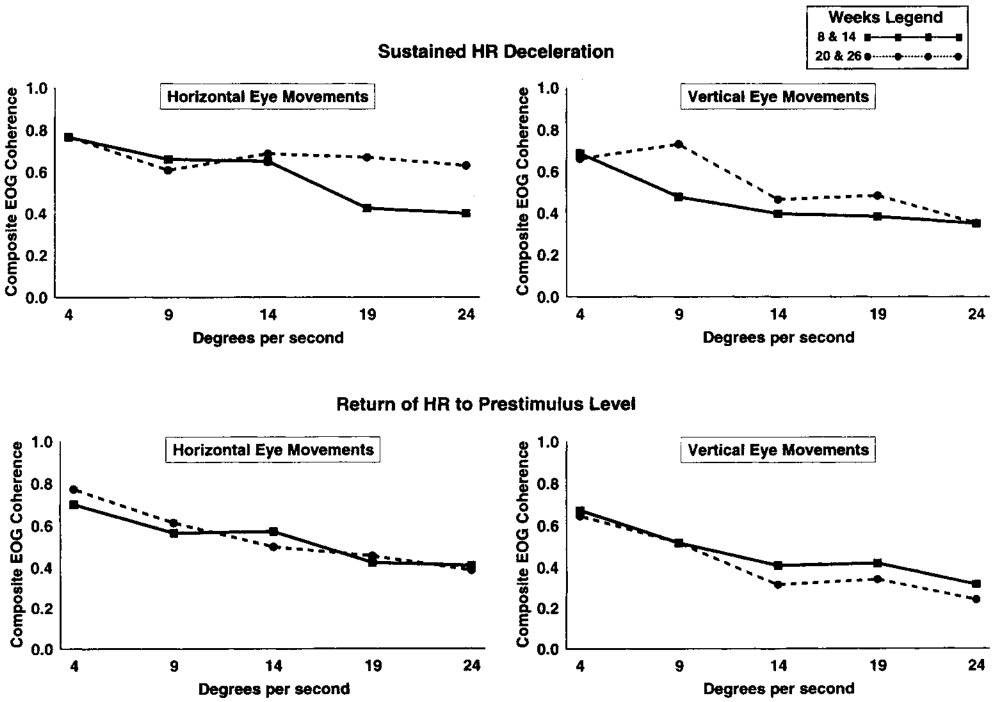

Figure 3. The coherence between the composite electrooculogram (EOG) signal and the tracking stimulus movement, as a function of stimulus tracking speed and testing age (8 and 14 weeks combined, 20 and 26 weeks combined), shown separately for the horizontal and vertical eye movements. The top two plots were taken from the period when sustained heart rate (HR) deceleration was occurring, and the bottom two plots were taken from the period after HR had returned to its prestimulus level.

ticularly at the highest stimulus speeds (19 and 24 deg/s). The effect of stimulus speed on tracking was similar for the four testing ages during the look onset phase and during the return of HR to prestimulus level. Thus, age changes in overall stimulus tracking occurred primarily during HR-defined sustained attention.

Smooth pursuit tracking (smooth pursuit EOG component). The coherence between the smooth pursuit component of the EOG and the tracking stimulus represents how well the stimulus is being tracked with smooth pursuit eye movements.

The effects of speed on smooth pursuit tracking were similar to those found with overall stimulus tracking. There was a decrease in smooth pursuit tracking (smooth pursuit EOG coherence) with increases in stimulus speed, $F(4, 131) = 27.78, p < .0001$. There was a slight difference in this speed effect for the HR-defined attention phases. For look onset and the sustained HR deceleration periods, the decline in smooth pursuit tracking was gradual and continuous over the five testing speeds. For the period when HR returned to its prestimulus level, the effect of speed was smaller, less continuous over the testing speeds, and occurred primarily as a large decrease from 4 to 9 deg/s. There were some age differences in the smooth pursuit tracking. Generally, however, these seemed to reflect idiosyncratic differences in the speed–coherence relation and were inconsistent in the pattern of developmental changes in tracking across stimulus direction or HR-defined phases.

Eye Movement Gain

The gain of the eye movements to the tracking stimulus movement was examined. The gain estimates how well the amplitude of the tracking stimulus was duplicated by the amplitude of the eye movements.

Overall stimulus tracking (composite EOG). The gain of the composite EOG signal to the tracking stimulus was analyzed. This represents how well the amplitude of the overall stimulus tracking (e.g., gaze, consisting of smooth pursuit and saccadic eye movements) matched the amplitude of the tracking stimulus. Figure 2 shows the gain for overall stimulus tracking in the total trial as a function of stimulus speed for the vertical and horizontal eye movements. Figure 4 shows the gain for overall stimulus tracking for the HR-defined sustained attention and the return of HR to prestimulus level, combined over horizontal and vertical eye movements, and for the testing ages (8 and 14 weeks combined, 20 and 26 weeks combined). Figure 4 also shows the gain for the smooth pursuit tracking eye movements.

There was a reliable effect of stimulus tracking speed on the gain of the composite EOG relative to the tracking stimulus movement, $F(4, 124) = 5.80, p = .0003$. Gain decreased with stimulus tracking speed (Figure 2). However, this speed effect differed among the phases. Overall stimulus tracking gain did not decline over the stimulus speeds at the beginning of the look (look onset) but did decline over the stimulus speeds later in the look (HR deceleration, return of HR to prestimulus level). The gain for

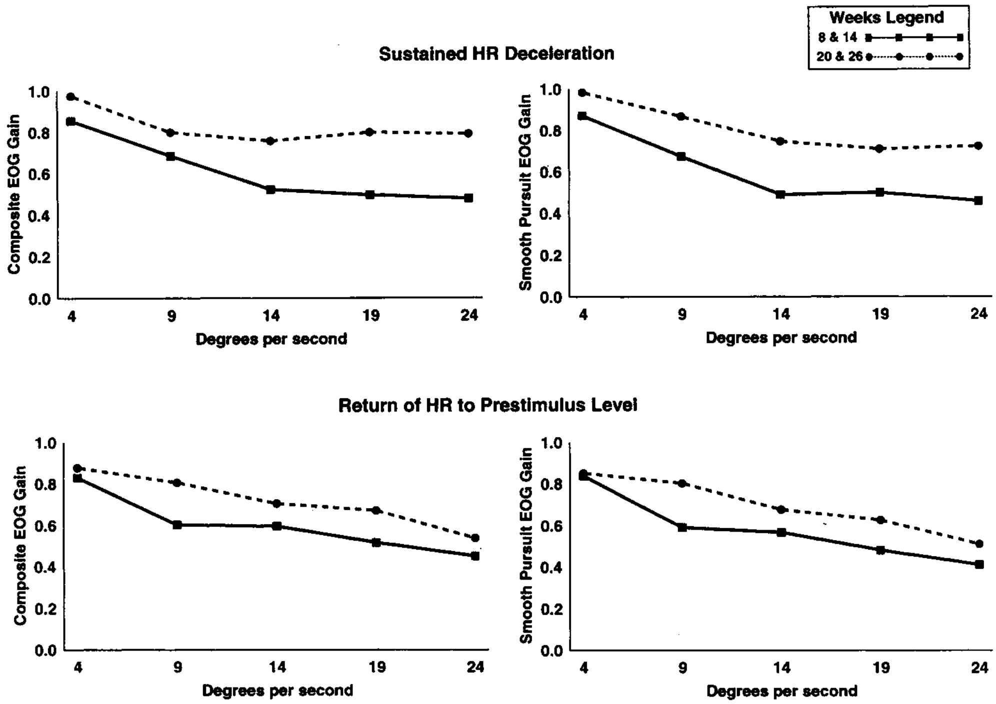

Figure 4. The composite electrooculogram (EOG) gain and smooth pursuit EOG gain over the tracking stimulus movement, as a function of stimulus tracking speed and testing age (8 and 14 weeks combined, 20 and 26 weeks combined), combined over the horizontal and vertical eye movements. The top two plots were taken from the period when sustained heart rate (HR) deceleration was occurring, and the bottom two plots were taken from the period after HR had returned to its prestimulus level.

the horizontal tracking stimulus was larger than the gain for the vertical tracking stimulus, $F(1, 35) = 5.61, p = .0235$, and this tended to occur at the three fastest tracking speeds (Figure 2). There was an effect of age on the gain of the overall stimulus tracking, $F(3, 36) = 8.70, p = .0002$. As with the coherence measure, there was an increase in gain from 8 to 26 weeks of age that was found primarily in the periods of sustained HR deceleration (Figure 4, for overall stimulus tracking and for smooth pursuit tracking). Overall stimulus tracking gain during the periods of sustained HR deceleration was equivalent for the four ages at the 4 deg/s stimulus tracking speed. Gain declined at a faster rate during higher stimulus tracking speeds for the younger ages than it did for the older ages. The two older ages had almost no decline in overall stimulus tracking gain over the five stimulus speeds for the horizontal tracking stimulus during this attentive period. This Speed × Age interaction during sustained HR deceleration was statistically reliable for the horizontal tracking stimulus, $F(12, 66) = 2.63, p = .0062$, whereas only the age effect was statistically reliable for the vertical tracking stimulus.

Smooth pursuit tracking (smooth pursuit EOG component). The gain of the smooth pursuit component of the EOG signal to the tracking stimulus was analyzed. This represents how well the amplitude of the smooth pursuit tracking matched the amplitude of the tracking stimulus. The pattern of results for the smooth pursuit tracking gain was nearly identical to that of the overall tracking gain.

Saccadic Tracking

Saccade frequency. The frequency of the saccades as a function of the experimental factors was analyzed. Figure 5 shows the number of saccades per 60 s as a function of stimulus speed, tracking direction, testing age (8 and 14 weeks combined, 20 and 26 weeks combined), and HR-defined attention phases. First, saccade frequency during tracking of the horizontal tracking stimulus was nearly twice as large as saccade frequency during tracking of the vertical tracking stimulus, $F(1, 36) = 26.68, p < .0001$. Second, there was an increase over the four testing ages in the frequency of saccades during horizontal stimulus tracking, $F(3, 36) = 4.08, p = .0136$, whereas there was no age difference in the frequency of vertical saccades. Horizontal saccade frequency during the look onset phase decreased as tracking stimulus speed increased (Figure 5), whereas horizontal saccade frequency during the sustained HR deceleration phase increased with increases in stimulus tracking speed (Figure 5, Sustained HR Deceleration).

Saccade amplitude. The amplitude of the saccades as a function of the different experimental factors was analyzed. Figure 6 shows the saccade amplitude as a function of the stimulus speed for the four testing ages, separately for the horizontal and vertical eye movements and combined over the HR-defined attention phases. There was an effect of age on saccade amplitude, $F(3, 36) = 2.99, p = .0435$. The age effect reflected an increase in the amplitude of the saccades over the four testing ages. There were some effects of the tracking stimulus speed on saccade amplitude. For the vertical saccades during the sustained HR deceleration,

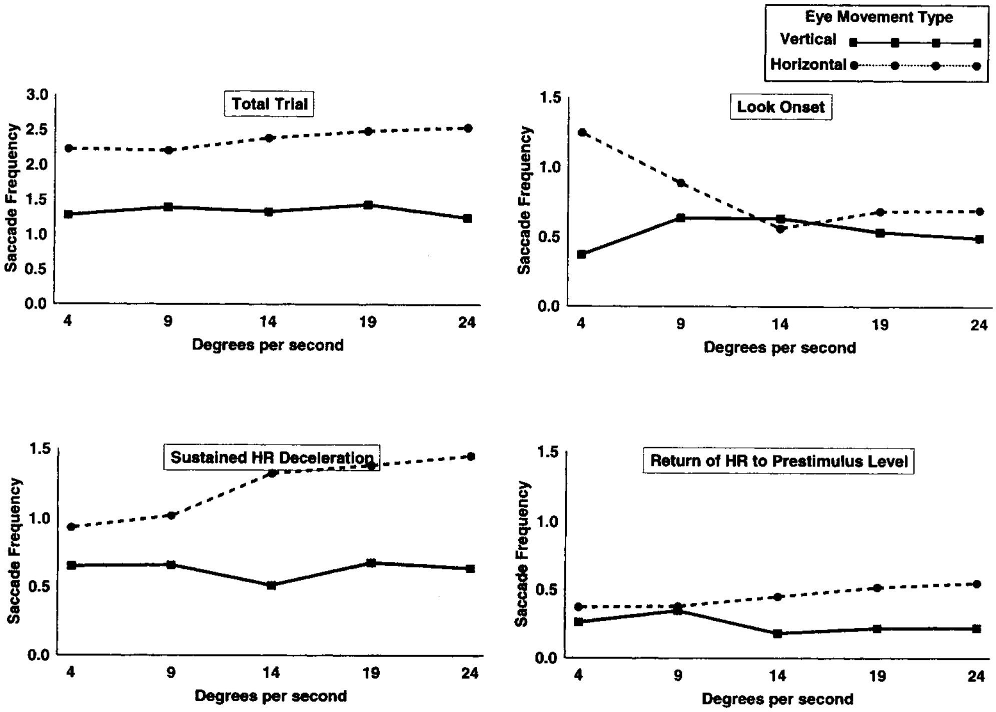

Figure 5. Saccade frequency (number of saccades per second) as a function of tracking stimulus speed and horizontal/vertical eye movements, shown separately for the heart rate (HR)-defined attention phase and combined over testing age.

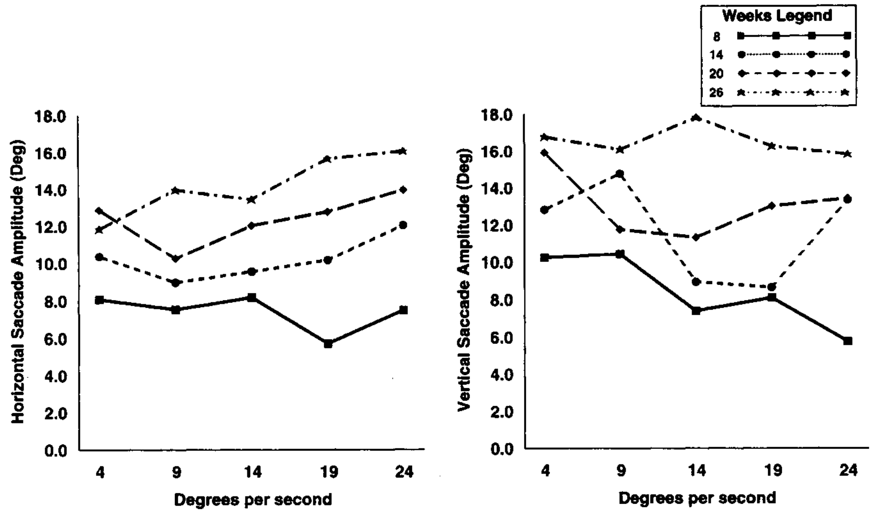

Figure 6. Saccade amplitude as a function of tracking stimulus speed and testing age shown separately for horizontal saccadic eye movements and vertical saccadic eye movements. Deg = degree.

there was a decrease in saccade amplitude over the first four tracking speeds. For the horizontal saccades, there was a fairly consistent difference in the testing ages in the relation between tracking stimulus speed and saccade amplitude. The slope relating the amplitude of the horizontal eye movements to tracking stimulus speed went from negative for the 8-week-olds to relatively flat for the 14-week-olds to positive for the 20- and 26-week-olds.

Discussion

We will summarize the results of this study. First, there was a reliable effect of the speed of the tracking stimulus on almost all measures of eye movement tracking. For the overall tracking eye movements and smooth pursuit eye movements, there were decreases in the ability to track the stimuli as the speed of the tracking stimulus increased. On the other hand, there was a positive relation between tracking speed and the measures of saccadic eye movements—saccade frequency and saccade amplitude. This suggests that with increases in tracking speed the infants switched from following the stimulus with smooth pursuit eye movements to saccadic eye movements. Second, there were differences among the four testing ages on these eye movement measures. There was an increase with age in overall tracking coherence, and an increase overall and smooth pursuit gain. This appeared for the smooth pursuit eye movements (coherence and gain) as a preservation of tracking as the speed of the tracking stimulus increased, so that the older age infants were affected less deleteriously by the higher stimulus speeds. For saccadic eye movements during tracking, there was actually a decrease in saccade amplitude with increases in tracking speed for the youngest age group, whereas the two older age groups showed an increase in saccade amplitude for tracking the stimulus as tracking speed increased. This suggests the switch from following the stimulus with smooth pursuit eye movements to saccadic eye movements at faster stimulus speeds is an ability that develops over this age range. Third, most of the findings just summarized occurred when HR was showing a sustained deceleration (or sustained lowered HR). This sustained HR change indicates that sustained attention toward the stimulus was occurring. Thus, the developmental changes in stimulus tracking occur primarily in conjunction with sustained attention development. Finally, there were several measures that suggest that whereas tracking of the vertical and horizontal stimuli were approximately equivalent, horizontal eye movements were accomplished better than vertical eye movements.

The most important finding of this study was that almost all of the age changes in stimulus tracking occurred when attention was engaged. The period of time after a significant deceleration has occurred until HR returns to its prestimulus level is thought to represent active attention engagement in the infant ("sustained attention"; Berg & Richards, 1997; Richards & Casey, 1992; Richards & Hunter, 1998). In this study, there were overall increases in smooth pursuit and saccadic tracking. This appeared for the smooth pursuit eye movements as a preservation of tracking level (coherence, gain) across increasing stimulus speeds for the older age infants and as an increase in saccade amplitude across tracking stimulus speeds for the older age infants compared with the youngest ages. These age changes occurred primarily or exclusively during this period of sustained attention. Smooth pursuit gain, smooth pursuit coherence, and saccade amplitude were actually larger during the look onset period (stimulus orienting) for the 8- and 14-week-olds than they were during the sustained attention period, whereas they tended to increase from stimulus orienting to sustained attention for the two oldest ages. This suggests that the age-related changes in smooth pursuit and saccadic tracking observed in studies such as Aslin (1981), Phillips et al. (1997), Shea and Aslin (1990), and von Hofsten and Rosander (1997) were primarily due to eye movements during sustained attention.

The measurement of sustained attention in this study also revealed developmental changes in how stimulus tracking was done at the different ages. For the 8-week-old infants, overall stimulus tracking (coherence), the amplitude of the gaze (gain), and the underlying components of gaze (smooth pursuit gain and saccade amplitude) decreased with increases in tracking speed from 4 to 24 deg/s. For the 14-week-old infants, overall stimulus tracking and gaze gain did not decrease as rapidly for faster stimulus speeds, and the decrease in smooth pursuit tracking at higher stimulus speeds was partially compensated by slight increases in saccadic amplitude. Finally, for the 20- and 26-week-old infants, especially during sustained attention, the measures of overall tracking and gaze were much less affected (coherence) or unaffected (gain) by tracking speed. However, there was a decrease in smooth pursuit tracking gain at the highest stimulus speeds (Figure 4, Sustained HR Deceleration) for which compensation was made by increasing saccade amplitude (Figure 6, Horizontal Saccade Amplitude). Thus, with increases in age over this age range, tracking during sustained attention was increasingly preserved over faster tracking stimulus speeds by shifting from smooth pursuit tracking to saccadic tracking when smooth pursuit tracking began to fail. The youngest ages did not show such an effect of attention. This seemingly qualitative shift in how tracking is done at the different ages seems to have occurred on the basis of quantitative shifts in the saccadic and smooth pursuit eye movement systems across this age range. Attention acted to enhance the underlying systems involved in this tracking and seemed to enhance the shift from smooth pursuit tracking to saccadic tracking as tracking stimulus speeds increased.

A comparison may be made between vertical and horizontal eye movements. This study found many similarities between the tracking of stimuli moving in the vertical and horizontal direction. Both types of eye movements showed an effect of the speed of the tracking stimulus and an increase over these four testing ages in the preservation of tracking characteristics (coherence, gain) over faster tracking speeds. Horizontal eye movements seemed to be more "mature" than vertical eye movements. This was shown in that coherence and gain measures of vertical eye movements decreased more rapidly with increases in tracking stimulus velocity than did similar measures of horizontal eye movements. Attention during stimulus tracking affected horizontal eye movements to a much greater degree than vertical eye movements. For example, at the three oldest ages, the overall tracking gain and the smooth pursuit gain did not decrease substantially over stimulus speeds during the HR deceleration period for the horizontal eye movements. There was a decline in both of these measures over tracking speeds for vertical eye movements. Number of saccades and saccade amplitude actually increased with increases in tracking stimulus speed for saccades during attentive tracking of horizontal stimuli, but remained constant (number of saccades) or decreased (saccade amplitude) for saccades during vertical stimulus tracking. Thus, horizontal eye movements and vertical eye movements differed in both their developmental course and their relation to attentive-stimulus tracking. A comparison of this study with previous studies cannot be made for vertical eye movements, because vertical eye movements have not been systematically studied in infants in this age range.

A possible limitation of the evaluation of vertical eye movements in this study, and the comparison of vertical and horizontal eye movements, was the different stimulus size in the horizontal and vertical dimensions (2° horizontal and 6° vertical). Originally, the infants were tested with a stimulus that was 2° wide × 2° high, but we found poor vertical tracking of this stimulus in pilot testing. The height of the tracking stimulus was increased to 6° in the vertical direction in an attempt to obtain comparable tracking behavior in the vertical orientation, though as noted, with mixed success. The larger vertical dimension probably resulted in poorer calibration of the EOG values to degrees than in the horizontal dimension because the fixation points at which calibration points were taken could be within 6° rather than 2°. This could have led to overall smaller coherence or gain values. Similarly, coherence and gain measures could have been smaller for the vertical eye movements, because gaze could have been on different parts of the vertical stimulus (within 6°) leading to larger variability in the relation between eye movements and stimulus movements. Total tracking eccentricity also differed between the horizontal and vertical orientations (44° horizontal and 33° vertical) due to the use of a standard TV monitor. This should not have affected the results of the comparison between horizontal and vertical tracking in a systematic way. The difference between the horizontal and vertical stimulus may have affected the results over ages or tracking stimulus speed, but should not diminish the findings of differential effects of attention on horizontal compared with vertical tracking stimuli.

Some of the results from this study may be compared fairly directly with that of a recent study by von Hofsten and Rosander (1997) and a study by Phillips et al. (1997). Von Hofsten and Rosander tested 9-, 15-, and 21-week-old infants, who tracked a horizontally moving 10° face stimulus at tracking speeds of 10, 20, and 40 deg/s. They reported gaze gains near 1.0 at almost all tracking speeds, whereas smooth pursuit gain was positively related to tracking speed. There was a change in the smooth pursuit gain-tracking–speed relation across this age. The composite EOG gains in this study were much lower and showed the expected decrease across tracking stimulus speeds. The smooth pursuit gains in this study were similar (about 0.2 units lower) to the von Hofsten and Rosander (1997) study and changed with age in a similar manner. Phillips et al. (1997) tested infants from 1 to 4 months of age, who tracked a horizontally moving light of 1.7°. Phillips et al. report pursuit gain levels very similar to those found in this study (e.g., at 2 months, about 0.9 for a 8 deg/s stimulus to 0.5 for a 24 deg/s; at 4 months, near 1.0 for 8 deg/s to 0.7 at 24 deg/s; cf. Figure 4 in the present study). Some of the differences between the von Hofsten and Rosander (1997) study and the Phillips et al. (1997) and the present study were probably due to the nature of the stimuli. The present study used a relatively simple and narrow stimulus (2° horizontal; cf. 1.7° in Phillips et al., 1997), whereas the stimulus used in the von Hofsten and Rosander (1997) study was a schematic face that was 10° wide. The smaller stimulus in the present study may have been more difficult to track than the large face. Several studies have shown that very large targets (6° to 16°) at slow speeds are tracked by infants at young ages (e.g., newborn, 1 month; Dayton & Jones, 1964; Hainline, 1988; Kremenitzer et al., 1979; von Hofsten & Rosander, 1996). We do not think that the differences in these studies were due to more attention elicited by the face. Under our most optimal attention condition, we still found a range of gaze gains and a gain-tracking–speed relation (e.g., Figure 4).

Some of the differences among these studies also may have been due to infant head movements. The experimenter restrained the infant's head movements in the Phillips et al. (1997) study, von Hofsten and Rosander (1997) allowed head movements and took them into account with quantitative measurements, whereas the present study allowed head movements but did not measure them. Infants generally track stimuli (and make eye movements to peripheral targets; Richards & Hunter, 1997) with a combination of head and eye movements. Our estimates of gain for smooth pursuit eye movements may have been artificially lowered because some of the tracking was done with head movements. This partially explains the difference between this study and the von Hofsten and Rosander (1997) study. The similar gains and tracking abilities found in this study and Phillips et al. (1997) suggest that other factors (e.g., tracking stimulus size) account for most of the differences in smooth pursuit tracking estimates between these studies.

The smooth pursuit eye movements in this study showed a continual increase in gain at the higher testing speeds with changes in age. This change in the gain-tracking–speed relation begins at birth and continues into childhood. For example, studies of newborns and infants younger than 2 months have found that gains at target velocities of about 10 deg/s were very low (e.g., < 0.5 in Roucoux et al., 1983; < 0.25 in Shea & Aslin, 1990). In the present study, at the two lowest speeds (4 and 9 deg/s) the smooth pursuit tracking gain was not significantly different over age, but at the faster tracking speeds (14, 19, 24 deg/s) noticeable age differences in tracking gain appeared. Smooth pursuit eye movements continue to develop through infancy and through childhood into adulthood (e.g., Accardo, Pensiero, Da Pozzo, & Perissutti, 1995). Accardo et al. tested children from 7–12 years and adults tracking a horizontal sinusoidal stimulus at speeds from about 6.4 deg/s to 38 deg/s. They found the children had smooth pursuit gains near 1.0 until about 25 deg/s, and then gain decreased as tracking stimulus speed increased. Adults, on the other hand, tracked at these speeds with smooth pursuit gains near 1.0 over all speeds. Under optimal conditions, adults may track targets fairly well up to speeds of 100 deg/s (Meyer, Lasker, & Robinson, 1985).

The findings of this study may be interpreted on the basis of recent models of the neural systems controlling infant eye movement development (Johnson, 1995; Johnson et al., 1998; Richards & Casey, 1992; Richards & Hunter, 1998). These models hypothesize at least three eye movement systems in the brain that show different developmental courses in this time frame. At birth, a reflexive saccade system, relatively unaffected by attention, dominates the control of eye movements. The early existence of this system explains the predominance of saccadic tracking of stimuli in the first 6–8 weeks. A second system controlling smooth pursuit eye movements involves cortical layers and cortical areas that show rapid postnatal development beginning around 6 to 10 weeks. Smooth pursuit eye movements therefore are relatively scarce or difficult to elicit before this age. A third system controlling targeted saccadic eye movements begins development near 2 months of age and develops rapidly from 2 to 6 months of age. The smooth pursuit and the targeted saccadic eye movement systems involve areas of the brain (e.g., posterior parietal cortex, Area MT [medial temporal]; Schiller, 1985, 1998) that are affected by attention, whereas the early reflexive saccadic system is relatively unaffected by attention. In the present study the age changes in smooth pursuit coherence and gain during attention and the increases in compensatory saccade amplitude during attention reflect the increasing influence of the smooth pursuit and targeted eye movement systems over this age range. The HR changes during attention index a general arousal system (Heilman, Watson, Valenstein, & Goldberg, 1987; Mesulam, 1983; Posner, 1995; Robbins & Everitt, 1995) that enhances the smooth pursuit and targeted saccade systems, and which itself shows developmental changes from 2 to 6 months of age (Berg & Richards, 1997; Richards & Casey, 1992). The simultaneous development of the eye movement systems (smooth pursuit, targeted saccades) and this general arousal system results in an increasing synchrony between attention and eye movement control. This synchrony was reflected in the present study in the increasing quality of the smooth pursuit eye movements, and in the age-related effect of attention on shifting tracking to the targeted saccadic system when smooth pursuit tracking began to deteriorate at higher tracking speeds.

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