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RESEARCH ARTICLE

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The development of reactive saccade latencies

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Abstract Saccadic reaction time (SRT) of 4-, 6- and 8-month-old infants' was measured during tracking of abruptly changing trajectories, using a longitudinal design. SRTs decreased from 595 ms (SE = 30) at 4 months of age to 442 ms (SE = 13) at 8 months of age. In addition, SRTs were lower during high velocities (comparing 4.5 and 9°/s) and vertical (compared to horizontal) saccades.

Keywords Infant · Saccade · Reaction time · SRT · Tracking · ASL

Introduction

A newborn child is unable to discriminate motion direction (Atkinson 2000) and track objects with smooth pursuit. They can, however, perform saccadic eye movements (Aslin 1986). This means that newborns can redirect gaze swiftly to new locations within the visual field. As infants grow older they become more proficient in combining saccades, smooth pursuit, and head movements to track moving targets (von Hofsten 2004).

Several studies have investigated the dynamics of saccade development, often during continuous tracking of sinusoidal trajectories (Gredebäck et al. 2005; Richards and Holley 1999; Phillips et al. 1997; Rosander and von Hofsten 2002; von Hofsten and Rosander 1996, 1997) In such tasks saccadic performance is most often described in terms of frequency and amplitude of saccades. Latencies of individual saccades cannot be reported since saccade initiation is not triggered by a specific external event but occurs as a consequence of insufficient smooth pursuit or in anticipation of future events (Leigh and Zee 1999).

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Within this paradigm numerous studies have reported that infants produce more saccades as task demands increase. von Hofsten and Rosander (1996) demonstrated that infants produced more saccades as the frequency of the stimulus motion increased (~1 saccade/s at 0.1 Hz and ~1.75 saccades/s at 0.3 Hz). Similar effects of frequency, as well as amplitude and velocity, have been reported elsewhere (Gredebäck et al. 2005; Phillips et al. 1997; von Hofsten and Rosander 1997). In a similar fashion, increasing the target frequency, amplitude, or velocity will enhance the amplitude (von Hofsten and Rosander 1997) and velocity (Phillips et al. 1997) of initiated saccades.

In addition, reliance on saccadic tracking appears to chance with age and be different for horizontal and vertical trajectories. Comparative studies of children and adults saccadic performance indicate that adult levels are not reached until children are between 10 and 12 years old (Yang et al. 2002). In younger infants saccade frequency has been reported to drop from ~1.75 saccades/s at 6.5 weeks to ~0.75 saccades/s at 12 weeks of age in response to small target whereas larger targets resulted in fewer saccades/s (target size ranged from 2.5 to 35°; Rosander and von Hofsten 2002). von Hofsten and Rosander (1997) also reported a decrease in saccade amplitude between 2 and 3 months of age (average saccade amplitude = 4.4° at 2 months and 3.4° at 3 months[1]) whereas Richards and Holley (1999) described an increase in saccadic amplitude between 2 and 6.5 months of age (from ~8 to ~16°) and a shift from smooth tracking to saccade reliance at high velocities. The later study presented infants with a vertical bar (2° horizontal ×6° vertical extension) moving on both horizontal and vertical trajectories.

Another study that investigated two-dimensional tracking in older infants reported an increase in saccade frequency between 6 months (from ~0 saccades/s at 0.1 Hz to ~0.5 saccades/s at 0.4 Hz) and 12 months

[1] Reported means are calculated from the group means presented in Table 2 of von Hofsten and Rosander (1997).

(~0.1 saccades/s at 0.1 Hz to ~1.2 saccades/s at 0.4 Hz) of age (Gredebäck et al. 2005). The same study also reported more vertical than horizontal saccades.

Some of the above mentioned effects converge; those that describe an increased reliance on saccades with increased task demands (defined by increased target velocity, amplitude, and frequency). Other results are less consistent, particularly effects of age and dimensionality (comparing horizontal and vertical tracking). Given the composite nature of the task (to use saccades, smooth pursuit, and head movements to keep gaze on target) it is difficult to evaluate whether these effects can be attributed to properties of the saccade system or if they arise as compensatory actions governed by, for example, changes in smooth pursuit proficiency.

Alternative approaches in which infants are presented with sequences of pictures that alternate between two locations engage the saccadic system in a more direct manner and enable reports of individual saccade latencies. In a series of studies, Canfield et al. (1997) investigated 2- to 12-month-old infants' saccadic reaction time (SRT) to static stimuli that alternated between different locations. In this study infants were presented with different sequences of left–right located pictures. These sequences ranged from highly predictable ones were the pictures alternated between two positions (L–R), sequences that included repetitions (L–L–R), and irregular presentations without a set sequence. Their conclusion was that infants average SRT decreased from 440 ms at 2 months to 285 ms at 12 months of age (see also, Rensink et al. 2000).

Substantially longer latencies for reactive saccades have been reported elsewhere (Aslin and Salapatek 1975; Bronson 1982). Bronson (1982) examined SRTs to peripheral targets and found that the SRTs equaled 1 s at 2 months of age and 0.5 s at 5 months of age. Aslin and Salapatek (1975) measured the latency and amplitude of 1- and 2-month-old infants' reactive saccades. They found that the SRT in both age groups depended on the size of the target offset. At 1 month of age, the median SRT ranged from 800 ms (10° offset) to 1,480 ms (30° offset). One month later a significant decrease was observed with corresponding SRTs being 480 and 1,280 ms. It thus appears that SRTs vary substantially over different tasks.

Measuring SRTs to repetitive stimuli, as described above, induce its own set of confounds. Richards (2000) demonstrated that priming effects emerge between 3 and 6 months of age in response to repetitive presentations of target locations. In addition, Wentworth and Haith (1992) reported that predictable cues were followed by a higher degree of anticipation and speedier reactions. As such, there appear to be two slightly different effects that both affect SRTs in response to repetitive static stimuli, both priming effects and an increased tendency to predict the next stimulus location. These effects might have lowered the average SRT in some studies.

The current study attempts to bridge the gap between these two paradigms by presenting 4-, 6-, and 8-month-old infants with targets that move on linear trajectories that suddenly alter their direction of motion. This gives us the opportunity to observe horizontal and vertical saccades during ongoing tracking [in accordance with the paradigm used by Gredebäck et al. (2005), von Hofsten and Rosander (1997) and Richards and Holley (1999)] and to measure SRTs of individual saccades [in accordance to the paradigm used by Canfield et al. (1997) and Bronson (1982)]. Abruptly changing the trajectory makes it possible to evaluate individual saccades fairly independent of smooth pursuit performance and since each trajectory is unique the risk of priming effects and predictive saccades are brought to a minimum.

Similar tasks have been successfully carried out with adult participants. In an influential study by Engel et al. (1999), adult SRTs were measured during continuous tracking of linear trajectories that suddenly altered their direction of motion. The target moved with one of two velocities (15 or 30°/s) and changed trajectory at a random position near the center of the screen to one of 11 alternative trajectories. In their study adult SRTs averaged 197 ms (SD = 28 ms).

Method

Participants

Sixteen infants participated in this longitudinal study (10 males and 6 females). They visited the lab at 4 months (126 ± 4 days), 6 months (178 ± 4 days), and 8 months of age (234 ± 8 days). Participants were contacted by mail based on birth records; before sending out the letters these were also checked by the health authorities to ensure that only families with healthy infants were contacted. The study was approved by the ethics committee at the Research Council in the Humanities and Social Sciences and therefore in accordance with the ethical standards specified in the 1964 Declaration of Helsinki. Before each session participating families were informed about the purpose of the study and signed a consent form. As compensation for their participation each family received either two movie tickets or eight bus tickets with a total value of ~20 €.

Apparatus

Infants gaze was measured with an infrared corneal reflection technique (ASL, Bedford, MA, USA) in combination with a magnetic head tracker (Flock of Birds, Ascension, Burlington, VT, USA). The ASL 504 calculates gaze from the reflection of near infrared light in the pupil and on the cornea (sampling frequency 60 Hz, precision 0.5°, accuracy < 1°). Head position was calculated from changes in an electromagnetic field generated by a magnet and detected by a small sensor (miniBird, 18×8×8 mm) attached to the Flock of Birds control unit with a cable. The ASL 504 camera moved with two degrees of freedom (azimuth and elevation) and was accessible via remote control and keyboard. During slow translations of the head and torso an auto correction function rotated the camera to the center of the eye. During fast translations and prolonged blinking, the ASL 504 utilized information from the Flock of Birds to relocate the eye.

Infants were presented with a 3D 'happy face' that moved over a blue colored screen. Its motion was controlled by two servomotors (one for horizontal and one for vertical motion). The motors controlled the target using two magnets, one attached to the engines on the back of the screen and the other to the target at the front of the screen. Both magnets were covered in cloth to reduce friction and ensure a minimum of movement related noise. A similar device has previously been used to produce moving objects on a screen (Hespos et al. 2002; von Hofsten and Spelke 1985; von Hofsten.et al. 1998). The steel sheath covered an area of 1 m^2 and 0.42 cm^2 could be used to produce stimulus motions. This presentation device was located 128 cm in front of the experimental booth. The side panels between the screen and the experimental booth was covered with thick black fabric to reduce external light sources.

Infants were seated inside a semi-enclosed experimental booth (106×122×204 cm). The stimulus was visible through an opening (30×30 cm) in one of the short walls of this booth; its lower edge was 100 cm from the floor. A shelf below the opening (82 cm from floor) held the ASL 504 camera unit. Outside the experimental booth a loudspeaker was located on each side of the opening. On the backside of the booth a Plexiglas frame held the Flock of Birds magnet. The miniBird sensor cable entered the booth through an opening in the same wall below the Flock of Birds magnet. Light-blocking curtains covered the entrance to the experimental booth to eliminate outside light from entering the booth.

Visual stimuli

A combination of a bell, a bright colored face, and a red light attached to a rod was used to attract the infants' attention during calibration. This stimulus was moved back and forth between the upper left and lower right corners of the screen during calibration. To test calibration quality this target moved around the screen, stopping at each of its four corners.

The experimental stimulus consisted of a head (yellow), a nose (blue), a painted mouth (red), and two glowing eyes (red LEDs) under black eye brows. Underneath the target and above the magnet was a paper circle (yellow and black) that effectively doubled the size of the target (radius = 1 visual degree). The current setup only used the lower half of the display screen (35×65 cm).

The target moved with one of two velocities (4.5 and 9°/s) starting from the upper right or the lower left corner of the screen. The initial trajectory was always diagonal and directed towards the center of the stimulus presentation area. From its starting position the target moved on the same diagonal trajectory for either 8.9 or 12.4 visual degrees, thereafter the target turned to a straight vertical or horizontal trajectory. Trajectories starting at the upper right corner of the screen shifted to either a linear upward or rightward motion. Stimuli starting in the lower left corner turned to either a leftward or downward motion. The distance between the turning point and the end location of the trajectory was 4.6, 6.4, 7.6, or 10.6 visual degrees (see Fig. 1).

After each trial the target moved to the new starting location of the next presentation. The next trial did not start until the infant attentively focused on the target. All in all, the target moved on 16 unique trajectories (2 starting locations × 2 velocities × 2 turning locations × 2 post-turning trajectories; horizontal and vertical) that were presented to each infant only once.

Procedure

Upon arrival at the lab parents were briefed about the purpose of the study. They were provided with a basic description on how the eye and head trackers worked, after which a consent form was signed. One of the parents was seated inside the experimental booth, facing the stimuli presentation device. Infants were fastened in an infant car safety-seat that was placed on the parent's lap facing the same direction. During the entire experimental procedure parents were encouraged to talk and sing to their infants. As a whole this procedure provided a safe and reassuring atmosphere for the infants with both parental closeness and an unobstructed visual field. Once the infant and parent were comfortably seated infants were dressed in a baby cap that held the miniBird. This head tracker was placed above the infants' right eye.

After this initial procedure, a number of steps were taken before the actual stimuli presentations could begin. The distance between the miniBird and the infant's eye as well as thresholds for cornea and pupil detection had to be set. This was followed by a two-point calibration procedure (upper left and lower right corner of the screen) and a four-point calibration test (each of the four corners of the screen). If the eye tracker did not locate the fixation inside the extended calibration stimulus at each of the four corners of the screen the entire calibration procedure was redone.

This entire procedure rarely took more than a minute. With the exception of the calibration procedure all above-mentioned preparations were accompanied by a real-life puppet show, intended to focus the infants attention forward. For a more thorough description of the general methods used, see Gredebäck and von Hofsten (2004).

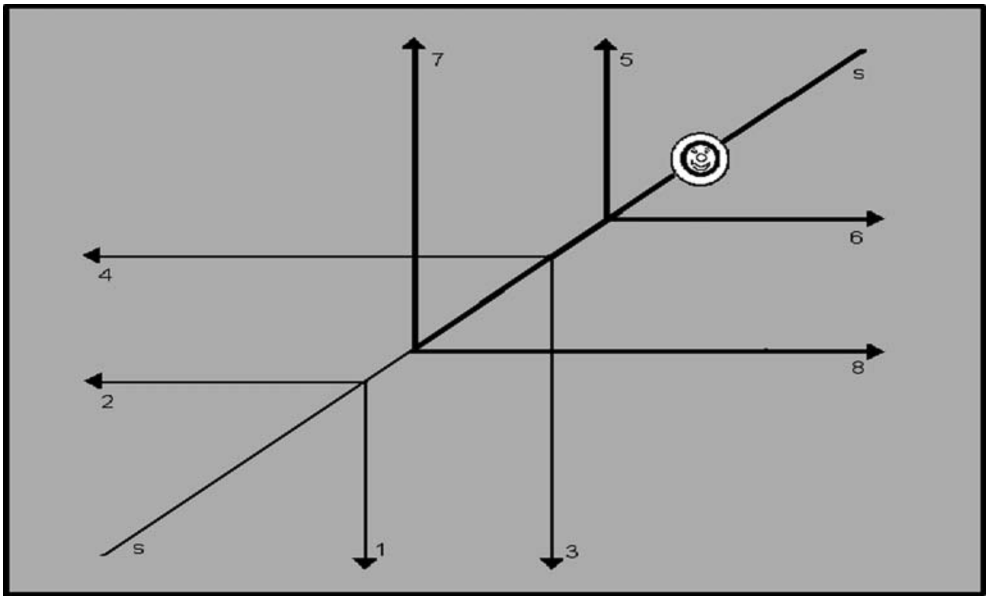

Fig. 1 Trajectories presented to the infants; *1–8* endpoints of the motion and *s* the starting points of the motion

During the stimuli presentations each of the 16 trajectories were presented to the infants in a randomized order. Lack of attention to any stimulus resulted in an additional presentation of that stimulus after the entire series. Each presentation lasted less than 5 s and all presentations rarely took more than 10 min.

Data analysis

Saccades were identified as eye movements with velocities of 30°/s or more. They were separately analyzed for vertical and horizontal dimensions. SRTs were based on the onset of the first saccade in the direction of the target's new trajectory following its directional shift (on either vertical or horizontal direction) with amplitude extending at least 1°.

The inclusion criteria limited the analyzed dataset to those trials in which target related smooth pursuit both preceded and succeeded the saccade. By this criterion we reduced the number of non-target related saccades and reduced noise.

Only horizontal components were analyzed for horizontal stimuli and vertical components for vertical stimuli. A multiple regression analysis of SRTs were performed with age (4, 6, and 8 months of age), velocity (4.5 and 9°/s), and dimension (horizontal and vertical saccades) as regressors. In the results, the mean SRT is reported, not the median. This is based on recommendations by Miller (1988) who argues against the median as a central measurement for small positively skewed samples, particularly if groups differ in size.

Results

One infant was excluded from the analysis due to lack of attention at both 4 and 6 months of age. Among the remaining 15 participants the independent variables (age, velocity, and dimension) were significantly associated with SRT, $r^2_{adj} = 0.21$, $F(4,142) = 13.87$, $P < 0.00001$. All regressors made significant individual contributions; SRTs decreased from 595 ms at 4 months of age (SE = 30; $n = 76$) to 485 ms at 6 months of age (SE = 23; $n = 105$) and 442 ms at 8 months of age (SE = 13; $n = 136$), (= −0.27, $t(142) = 12.4$, $P < 0.00001$.

In addition, both higher target velocities, (= −0.31, $t(142) = -4.3$, $P < 0.00005$, and vertical saccades, (= −0.22, $t(142) = -3.0$, $P < 0.005$, are related to lower saccadic latencies. These effects are visible in Fig. 2a, b. Figure 2c displays individual SRTs at each age. The correlation between SRTs at 4 and 6 months equaled 0.51, this correlation decreased to 0.22 when comparing 4- and 8-month-old infants and to −0.15 when comparing 6-and 8-month-old infants.

Discussion

When infants track a moving target that abruptly changes its direction of motion they produce a corrective saccade in order to fixate the target and continue smooth pursuit tracking. The current paper describes how the ability to reorient gaze in this way develops between 4 and 8 months of age, with a focus on saccadic latency. All in all, SRTs decreased as infants got older. In addition, both the velocity of the target and whether infants performed a horizontal or vertical saccade influenced SRT. Each of these effects will be discussed separately below, starting with age differences.

Age differences

Tracking studies have reported many changes in saccade usage, as infants grow older. Some studies have reported

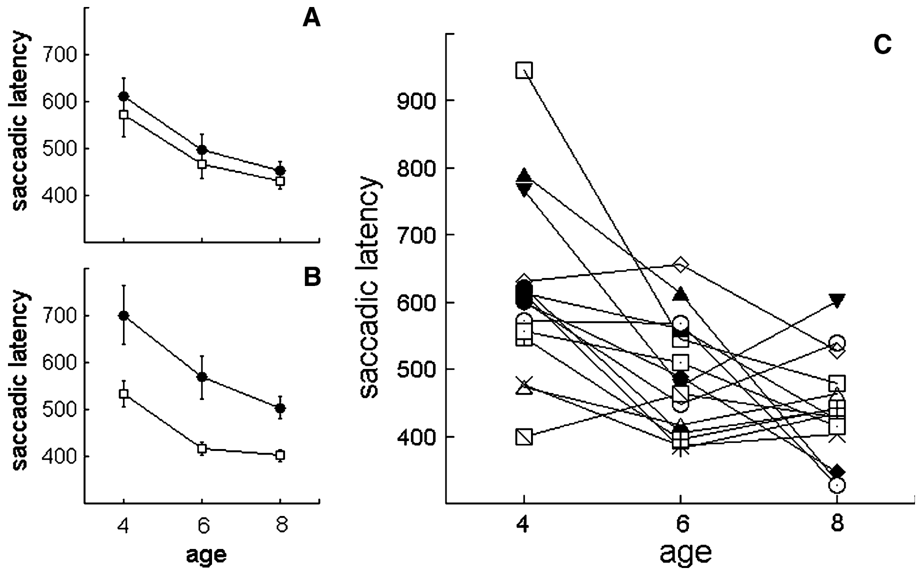

Fig. 2 Saccadic latency at each age (4, 6, and 8 months) divided into **a** horizontal (*closed circles*) and vertical (*open squares*) corrective saccades, **b** target velocity (4.5°/s = *closed circles* and 9°/s = *open squares*), and **c** individual data (average saccadic latency at each age)

a decrease in frequency and amplitude of saccades during the first few months of life (von Hofsten and Rosander 1997; Rosander and von Hofsten 2002). Others have reported the opposite results (Gredebäck et al. 2005; Richards and Holley 1999). It is difficult to relate these diverse findings to the current study. It is perhaps more fruitful to relate the current age effects to those found by Canfield et al. (1997). In their study SRTs decreased from 400 ms at 2 months to 285 ms at 12 months. Both of these values are lower than the average performance reported above (595 ms at 4 months and 442 ms at 8 months).

It is possible that the reported differences can be attributed to differences in the predictability of the targets. The current study presented infants with 16 novel trajectories without repetition whereas Canfield et al. presented pictures that alternated between two locations (L–R). During highly predictable presentations the location of the next picture could be determined from the previous locations (L–R). Even during irregular sequences any random saccade would have had a 0.5 success rate, because there were only two stimulus locations.

In fact, a number of studies have reported that repetitions decrease SRT. Richards (2000) demonstrated that attention to locations other than those fixated (as measured by saccade response facilitation) emerges between 3 and 6 months of age. In a study by Johnson et al. (1994) SRTs decreased with experience in 4-month-old infants. Their interpretation was based on a facilitation of covertly attended locations, places that held cues for future target appearances. Wentworth and Haith (1992) demonstrated that a picture, which strongly predicted the location of the next picture, was followed by a higher rate of anticipation and speedier reactions than demonstrated at baseline in 2- and 3-month-old infants. Likewise, Canfield and Haith (1991) found similar effects; they reported that infants at 3 months of age decrease their SRT over presentations.

This difference between repetitive and non-repetitive stimuli provides a good illustration of infants' predictive abilities and how important it is for researchers to relate their findings to infants' expectations and the development of predictive mechanisms.

Horizontal and vertical saccade latencies

The current study reports that infants' SRTs are lower for vertical than horizontal saccades. Richards and Holley (1999) reported more horizontal than vertical saccades but used a non-uniform stimulus that could account for differences between vertical and horizontal dimensions. Few other studies have reported on vertical and horizontal tracking in infancy. Gredebäck et al. (2003) measured gaze in response to circular trajectories. Nine-month-old infants displayed a higher gain (with higher variance) and larger lags with vertical gaze. Gredebäck et al. (2005) reported similar effects. In this study, infants also produced more vertical that horizontal saccades. These saccades were responsible for 41% of gain in vertical components of a circular trajectory, compared to 21% for horizontal components; see Collewijn and Tamminga (1984) for similar effects in adults.

The argument has been brought forward that differences in timing of both gaze and smooth pursuit tracking is due to differences in experience. According to this argument, (1) horizontal motion is more common than vertical, (2) infants produce more smooth horizontal tracking as a consequence thereof, and (3) this increased experience give rise to enhanced performance (Gredebäck et al. 2003; Gredebäck and von Hofsten 2004).

The same argument could possibly be applied to a higher reliance on saccades during vertical tracking. (1) We know that an infants' smooth vertical tracking is inferior to smooth horizontal tracking, (2) this results in a high dependency on vertical saccades (Gredebäck et al. 2005). (3) This increased experience might give rise to enhanced performance, as defined by facilitated SRTs.

If this (admittedly speculative) argument is valid then the current results provide a nice illustration of the importance of experience to ocular performance. It also highlights the strong functional dependency that each component of gaze tracking (in this case smooth pursuit and saccades) has on the development and execution of other components.

Velocity

It is difficult to discuss velocity related effects since numerous variables by definition co-vary with different velocities. It is highly likely that there exists an optimal tracking velocity and that performance decreases on both sides of this point (curvilinear effect). Finding shorter latencies at 9°/s (compared to 4.5°/s) could indicate that the higher velocity is closer to this optimal velocity.

On the other hand, it is equally likely that this difference is due to changes in the attractiveness or salience of the stimuli. In fact, Hainline et al. (1984) demonstrated that the attentional value of presented stimuli has a clear effect on saccade dynamics. Regardless of which of these accounts produced the high velocity proficiency found in the current paper we can conclude that it is essential to include multiple velocities in studies of infants' saccadic latencies.

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