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Smooth pursuit in infants: maturation and the influence of stimulation

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ABSTRACT

Purpose To investigate the development of smooth pursuit in infants and to assess the influence of different stimulus characteristics.

Methods A total of 131 eye movement recordings were obtained from 71 infants between 1 and 18 months of age using infrared photo-oculography. Smooth pursuit eye movements (SPEM) were stimulated using targets of different sizes (1.2° and 4.7° of visual angle) and velocities (7.5°/s, 15°/s and 30°/s).

Results Smooth pursuit maturation peaked between 2 and 6 months of age with smooth pursuit gain showing a steep rise for all stimulus velocities and target sizes within this age range ($p<0.0001$). Higher stimulus velocities were associated with shorter durations of the longest smooth pursuit ($p<0.0001$) and higher saccadic frequencies ($p<0.0001$). A larger stimulus size led to an increased saccadic frequency ($p=0.035$). Tracking time was highest when the larger stimulus of 4.7° of visual angle was applied ($p=0.022$) and when it moved at a medium stimulus velocity of 15°/s ($p=0.0002$). The choice between a schematic face and a scrambled face did not influence the quality of the infants' smooth pursuit.

Conclusion SPEM show an intensive maturation between 2 and 6 months of life. By 6 months of age SPEM have already reached an almost adult-like gain of 0.8 or higher. Further maturation is slow and still incomplete by the age of 18 months. Stimulus velocity and size have an important impact on the smooth pursuit quality, which should be considered in smooth pursuit testing in infants.

INTRODUCTION

Smooth pursuit is an indicator of visual maturation in infants. Smooth pursuit eye movements (SPEM) are stimulated by a movement of an image across the retina and, together with catch-up saccades, constitute visual tracking. The purpose of SPEM is to stabilise moving objects on the retina and thereby to enable perception of object details. Although several studies have reported the development of smooth pursuit in infants, there is controversy concerning the age of first presentation, the main age range of SPEM development and the age when adult SPEM values are reached.

Some studies have reported on first presentation of SPEM in neonates.[1–5] Others have linked it to foveal maturation and therefore to the age of 2–3 months.[6–8] On the one hand SPEM maturation has been proposed to be a continuous process during infancy and on the other hand substantial development during the first 3 months has been suggested.[9 10] Furthermore, there is a debate over whether cognitive stimuli (faces) trigger SPEM in infants earlier than non-cognitive stimuli.[11] The discrepancy between study results can most probably be ascribed to the application of different stimulus parameters. Studies that have detected SPEM in neonates have generally applied larger targets than studies that described the onset of SPEM only at a later age. Our aim was to investigate the influence of varying stimulus size, velocity and target recognition on SPEM in infants. Identification of variables that affect SPEM in infants will assist in making comparisons between studies and help eliminate present discrepancies.

METHODS

Participants

Eye movement recordings were performed in 89 healthy, term-born infants (42 boys and 47 girls) with a mean gestational age of 39.2 weeks. Recordings from 18 infants were discarded because of insufficient compliance. From each of the remaining 71 children one to five recording sessions were obtained between the ages of 1 and 18 months with the result that 131 recording sessions were obtained and evaluated (29 infants had one session, 28 had two sessions, 12 had three sessions, and two had five sessions). The infants were examined in Prechtl's state III (calm wakefulness with open eyes, regular breathing, absence of gross body movements).[12] At each session an ophthalmological examination was performed, including grating acuity by preferential looking, ocular alignment with the Hirschberg test, fusion with the four prism dioptres base-out test and pupillary reaction.

Recording equipment and procedures

Eye movements were recorded from the right eye, under binocular viewing conditions, with a photo-oculographic technique developed for examination of infants (Metrovision, Pérenchies, France).[5] This setup has been described in detail in a previous study investigating smooth pursuit in infants.[1] In brief, the eye is illuminated with infrared light (880 nm) using a dichroic filter (or hot mirror) allowing separation of visible light (to view the display) and infrared light (to record eye movements). Corneal reflection and pupillography are used to derive horizontal and vertical eye movements at a sample rate of 30 Hz with a horizontal range of ±30° and a resolution of 10 arc min.[13] Calibration is achieved using the geometry of the anterior chamber and is estimated from biometry data of 20 eyes of subjects aged between 3 and 7 years.[14] The subject was seated in an infant car seat 30 cm from a cathode-ray tube (CRT) monitor where stimuli for SPEM were generated using proprietary software included in the Metrovision system. They were presented upon a uniform grey surface of equal mean luminance of 5 cd/m^2, with a contrast between target and background of 95%. To minimise movements the head was placed between two soft cushions.

To investigate the effect of target size on SPEM, two different stimulus sizes were used: a black small square of 1.2° of visual angle, referred to as 'dot', and a large square of 4.7° with a black and white checkerboard pattern, referred to as 'square' (figure 1A). A schematic face was created to serve as a cognitive stimulus, referred to as 'face' (see figure 1A). To obtain a non-cognitive target a stimulus of the same size and contrast, and containing similar spatial frequencies, was generated, referred to as 'scrambled face' (see figure 1A). These were created to investigate target identification, following similar methodology to previous infant studies.[11]

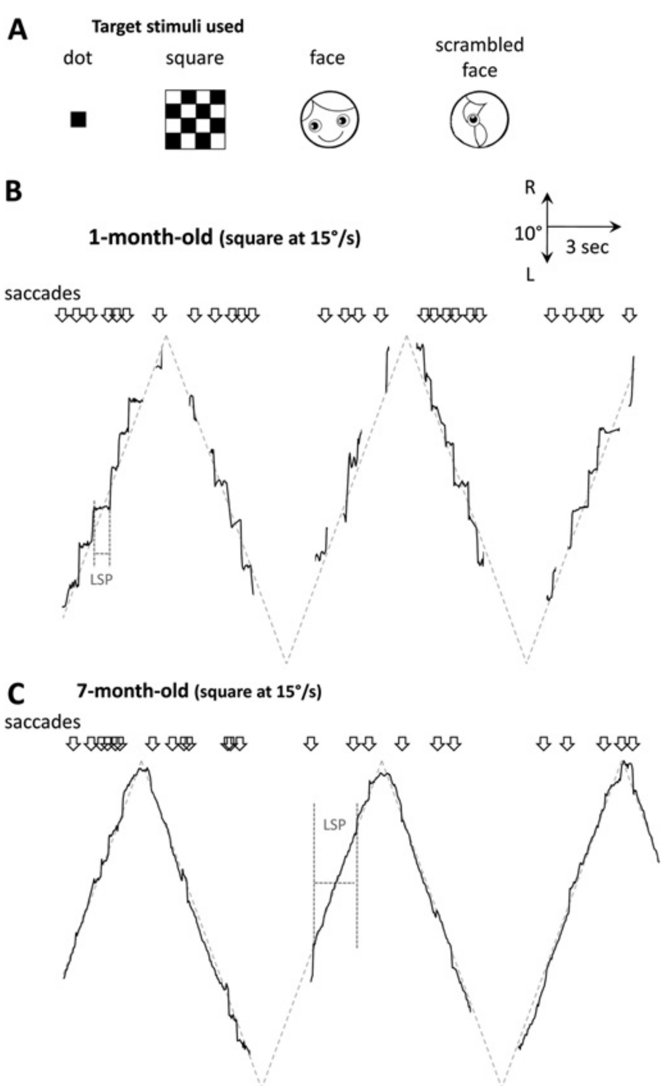

Figure 1 (A) Targets presented to investigate the influence of stimulus size (dot=1.2°, square=4.7°) and of possible recognition (face, scrambled face). Original horizontal eye movement recordings of (B) a 1-month-old infant and (C) a 7-month-old child following the square stimulus moving at a velocity of 15°/s. Eye movements are indicated by the black lines with movements to the right upwards on the traces and vice versa. The grey dashed line show the target movement. The arrows indicate catch-up saccades. The longest smooth pursuit (LSP) had a gain of 0.01 in the 1-month-old and 0.97 in the 7-month-old.

The stimuli moved horizontally at a constant velocity of 7.5°/s, 15°/s and 30°/s, using a triangular waveform profile, with an extent of ±28°, from the right to the left margins of the screen. Each stimulus was tested for a total time of 38 s. The slow phases were distinguished from the fast phases (saccades) by applying a velocity threshold of 60°/s for saccades. We evaluated the following five variables: (1) the duration of the longest smooth pursuit measured during each trial (in general preceded and succeeded by a saccade); (2) the smooth pursuit gain (eye velocity during the longest single smooth pursuit movement divided by the stimulus velocity); (3) mean velocity, that is the mean velocity during the total time of the non-saccadic eye movements; (4) saccadic frequency, defined as the number of saccades per second; and (5) tracking time, defined as the complete time during which the subjects attended to the target whether using SPEM, fixational eye movements or fast saccades.

Since attention time is limited in infants, the majority of recording sessions consisted of a small number of trials. Beyond the age of 12 months it became more difficult to keep the child's attention on the presented target. To confirm that the eye movement set-up was operational, the first stimulus applied was pre-selected with the aim of eliciting a robust response that could be seen on the online recording (one of the large stimuli consisting either of a square or sketched face stimulus applied at 15°/s). After this, stimuli were offered in a randomised order. The total number of each successful test applied was n=96 for the square, n=84 for the sketched face, n=42 for the dot and n=37 for the scrambled face (in total n=64 at 7.5°/s, n=110 at 15°/s and n=85 at 30°/s). If no attention was drawn to a stimulus, eye movement analysis was categorised as unsuccessful and not analysed. Once the sequence was finished or the infant was not interested in the target anymore, a different stimulus was displayed.

Statistical analysis

Linear mixed models were used to investigate the effect of age, stimulus velocity and stimulus on the SPEM parameters. To investigate the effect of age the data were grouped into the following age bands: 3 months (<4.5 months), 6 months (4.5–7.5 months), 9 months (7.6–10.5 months), 12 months (10.6–15 months) and 18 months (>15 months). Post hoc analysis using the Bonferroni method was used to compare differences between groups. Comparison of dot versus square and cognitive versus non-cognitive stimuli was performed in separate analyses. Curve fitting was applied to data showing the development of pursuit gain with age using the non-linear regression curve-fitting algorithms included in GraphPad Prism (GraphPad Software, La Jolla, California, USA). This method seeks to model the data by minimising the sum of the squares of the residuals (indicated by an increase in r^2) after applying best-fit curves commonly encountered in biological data. The development of pursuit gain with age was modelled with a sigmoid curve with a variable slope fixing the minima at 0.0.

RESULTS

The number of recording sessions (and number of viable trials overall) in each age band was n=34 (n=76) for 3 months, n=40 (n=85) for 6 months, n=27 (n=54) for 9 months, n=19 (n=33) for 12 months and n=11 (n=20) for 18 months, respectively. Some trials (12.1%) were classified as unsuccessful because attention was not drawn to the stimulus; 2.7% of trials were discarded because the eye movement recordings were of poor quality.

 Pieh C, Proudlock F, Gottlob I. *Br J Ophthalmol* (2011). doi:10.1136/bjo.2010.191726

Development with age

Smooth pursuit showed a profound development within the first 6 months. Pursuit was very saccadic and of extremely low gain at the age of 1 month. At 7 months smooth pursuit was less interrupted by saccades and the longest smooth pursuit had already reached a gain of close to 1 (figure 1). Sigmoid curves were fitted to data for change in pursuit gain with age for each stimulus velocity as shown in figure 2. In comparison to applying linear best-fit lines to the data, applying a sigmoid curve resulted in r^2 increasing from 0.097 to 0.24 for 7.5°/s, from 0.14 to 0.26 for 15°/s and from 0.18 to 0.22 for 30°/s. The gain increased rapidly and showed a steep rise between 2 and 6 months of age for all stimulus velocities and target sizes. The age of the steepest increase varied depending on the stimulus velocity, with the curve taking longer to reach a gain of 0.8 or higher for the 30°/s stimulus compared with the two stimulus velocities. Some infants reached a gain of 1 or even slightly higher. There were no reverse catch-up saccades (ie, in the opposite direction to the SPEM) on examination of the original traces of individuals with pursuit gains greater than 1.0. No further significant increase in the velocity gain was measured until the age of 18 months. In addition, longest smooth pursuit increased (p=0.002) and saccadic frequency decreased (p=0.0007) significantly with age (figure 3). There was no significant change with tracking time and age (p=0.50). However, of the 18 discarded recordings, 12 were of children ≥12 months, which explains the reduced number of recordings beyond 12 months of age.

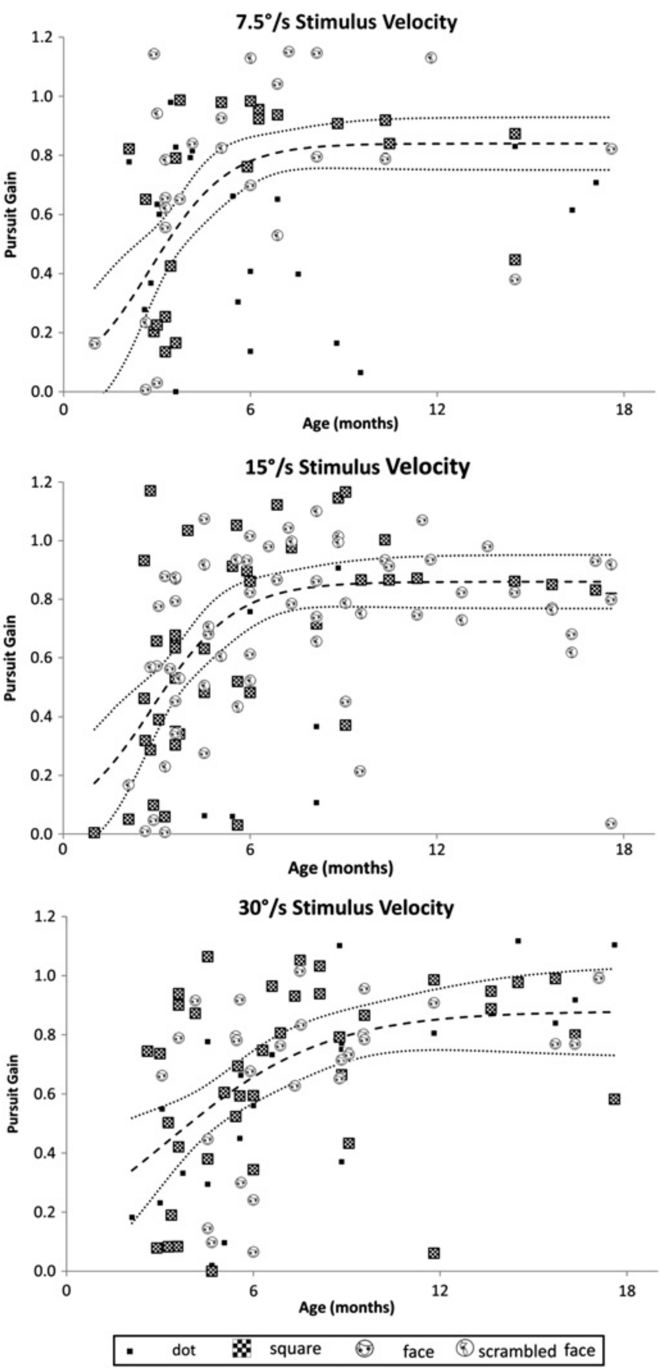

Figure 2 Development of smooth pursuit gain with age for all three stimulus velocities (7.5°/s, 15°/s, 30°/s) and the four applied target types (dot, square, face, scrambled face).

Target influence on smooth pursuit parameters

Overall, the duration of the longest smooth pursuit decreased significantly with increasing stimulus velocity (figure 4A). The stimulus size and the application of a cognitive stimulus did not significantly influence the gain of the longest smooth pursuit or mean velocity (table 1). In general, the saccadic frequency increased with the stimulus velocity (figure 4B) and was higher for the square compared with the dot. There was no significant difference between the cognitive and the non-cognitive stimulus. Tracking time depended on the stimulus velocity and was highest for 15°/s (figure 4C). Further, it was significantly higher when the infant had to follow the square in comparison to the dot. No difference of attention was observed between the cognitive and the non-cognitive stimulus.

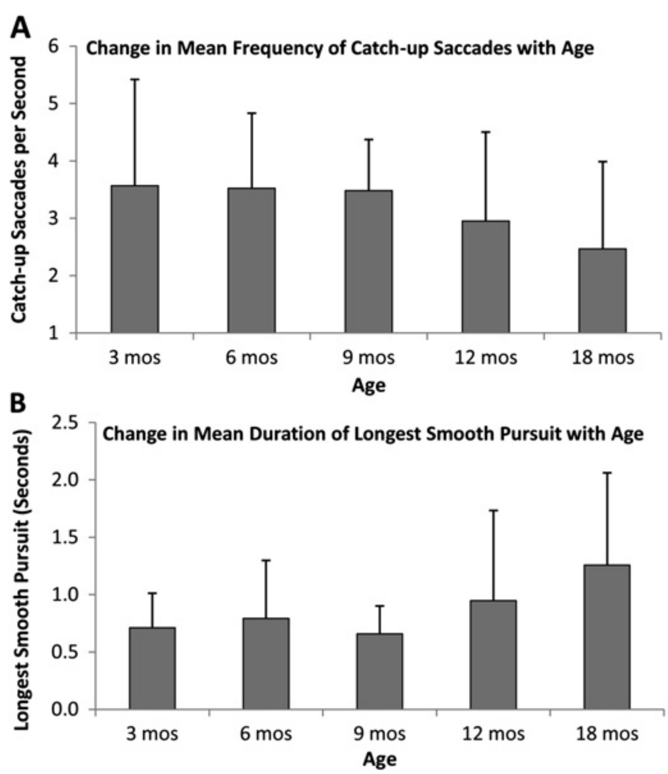

Figure 3 Change in the (A) frequency of catch-up saccades and (B) duration of longest smooth pursuit with age. Means for all stimulus conditions are shown and error bars indicate SDs.

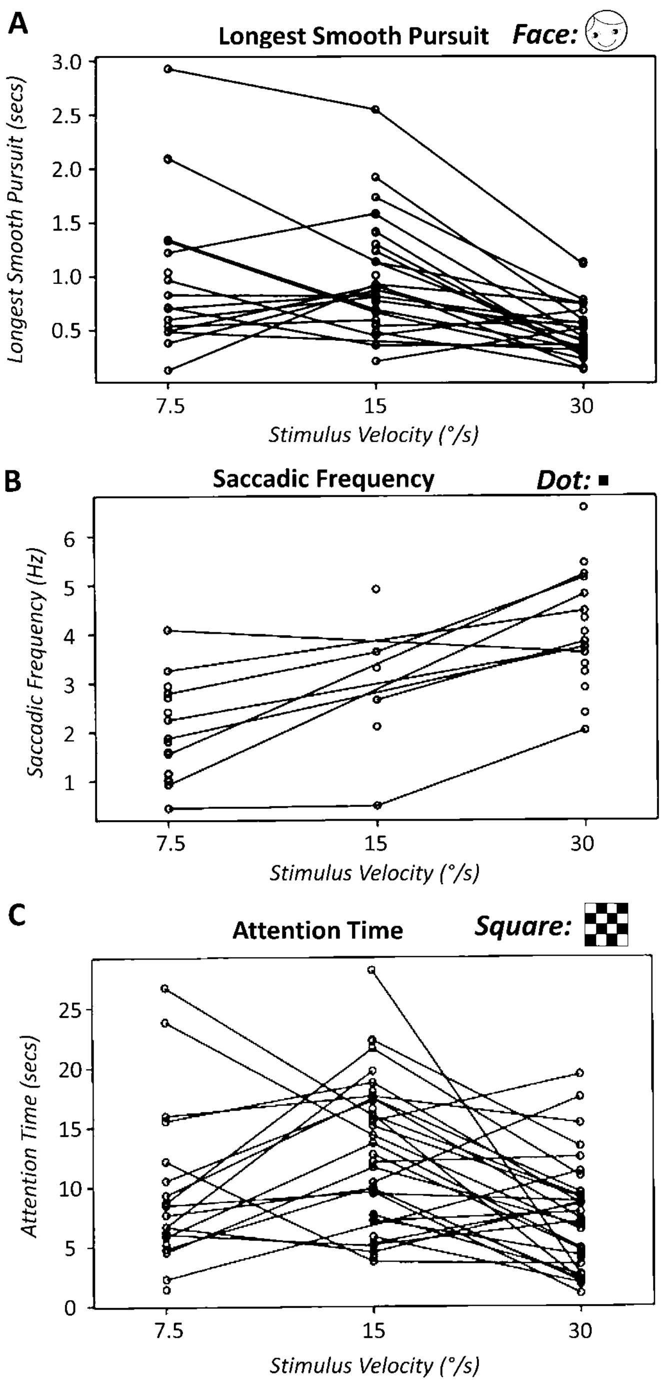

Figure 4 The effect of stimulus velocity on (A) the duration of the longest smooth pursuit for the face stimulus (B) the saccadic frequency for the dot stimulus and (C) the attention time for the square stimulus.

DISCUSSION

Our findings confirm a rapid maturation of the smooth pursuit system within the first 2 and 6 months of age in a large cohort of infants. For higher stimulus velocities the duration of the longest smooth pursuit was shorter and the saccadic frequency higher. A larger stimulus size led to an increased saccadic frequency. Tracking time was greatest when the larger stimulus of 4.7° of visual angle was applied and when it moved at a medium stimulus velocity of 15°/s. The choice between a cognitive and a non-cognitive stimulus did not influence the quality of the infants' SPEM.

Studies on the development of SPEM are rare and mostly performed in a small cohort over a limited period of time.[1 9 10 15 16] Results are controversial. One study describes the presence of slow and inaccurate SPEM after the first few months of life.[16] Another study describes stable SPEM with high gain during the first 4 months of life.[1] Rütsche *et al* for a triangular stimulus waveform found SPEM development within the first year up to a mean gain of 0.5. Not until later, between 1 and 3 years of age, was an increase in SPEM gain from 0.5 to 0.8 found.[9] In contrast, von Hofsten *et al* and Jacobs *et al*, also applying a triangular waveform, found that SPEM developed much earlier. von Hofsten *et al* observed SPEM developing rapidly in 11 infants between 2 and 3 months of age, reaching a gain of 0.8 thereafter.[15] Similarly, Jacobs *et al* found an intensive gain development during the first 3 months of age up to 0.8.[10] In our cohort the mean gain was still 0.8 at 18 months of age and had not yet reached adult levels of 1.0.[17] It is possible that SPEM development described for younger ages may be associated with larger stimulus sizes and slower velocities applied in these studies. However, stimulation with large targets could also elicit an optokinetic reflex instead of smooth pursuit. This is known to be present in newborn infants because of the existence of subcortical as well as cortical mechanisms.[4]

Brain areas related to smooth pursuit include the cerebellum (flocculus, dorsal vermis and fastigial nucleus), medial superior temporal cortex, pontine nuclei, caudal frontal eye-fields (FEF) and supplementary eye-fields (SEF). Since FEF and SEF are known to be involved in SPEM gain,[18 19] the intensive development between 2 and 6 months old may reflect profound maturation of the frontal cortex during this period. This is consistent with the maturation of other oculomotor parameters including saccadic accuracy and optokinetic symmetry.[20 21] In contrast the sensory system, in particular the fovea, matures up to 11–15 months of age.[22]

We found stimulus velocity influences gain development only during the first few months of life with slower development of SPEM gain associated with the fastest stimulus velocity applied. Our findings confirm previous studies, where faster stimulus speeds are associated with reduced gains during the first months.[10 23]

Table 1 p Values for statistical analysis where age, stimulus velocity and stimulus type were included as factors

Variable	Age (3, 6, 9, 12, 18 months)	Stimulus velocity (7.5°/s, 15°/s, 30°/s)	Stimulus: Dot versus Square	Stimulus: Cognitive versus non-cognitive
Longest smooth pursuit	0.002*	<0.0001*	0.872	0.343
Gain during longest smooth pursuit	<0.0001*	<0.0001*	0.255	0.137
Mean velocity	0.255	—	0.224	0.994
Saccadic frequency	0.0007*	<0.0001*	0.035*	0.146
Attention time	0.489	0.0002*	0.022*	0.693

*Significant values.

Except for an increased saccadic frequency for the larger stimulus, target size had little influence on the smooth pursuit quality in our study. Possibly 1.2° and 4.7° might have been too similar in size to evoke a difference in the infant's pursuit. Jacobs *et al* applied a large target of 18.5×14.5 cm at 50 cm distance and found an intensive gain development up to 0.8 during the first 3 months.[10] The influence of the target size, therefore, cannot be excluded entirely. The influence of the target size on the saccadic frequency during SPEM has been previously reported.[18] Infants aged 6 to 9 weeks make more saccades when following a target of 2.5° visual angle compared with 35°. This effect was not observed in 12- and 15-week-old infants.

There was no difference between the SPEM of the schematic face serving as a cognitive stimulus and the scrambled face. Since it is uncertain whether the schematic face applied was recognised by the infants, the results need to be interpreted with caution. Other studies have applied photographic representations of human faces in comparison to phase-scrambled faces to investigate recognition.[24] Photographic stimuli are less abstract and probably easier to recognise by infants compared with the stimulus used in this study. However, the stimuli used here contain well-defined contours of high contrast, which are less likely to be susceptible to motion blur when moving at faster velocities. Other studies have shown a preference for schematic faces over scrambled faces only after the age of 1 month.[25 26]

A limitation of the study was the smaller number of successful recording sessions and viable trials in the older age groups. This study follows essentially a cross-sectional study design allowing for repeated measures rather than using a longitudinal study design. The latter form of study design can be more powerful when serial recordings are attained in equal numbers across all age intervals. However, the poor compliance in the older age group becomes even more problematic for this type of study design due to data not being missing at random. In addition a larger number of recordings in infants below 2–3 months of age would have been of benefit in improving the fitted model of the data at younger ages.

CONCLUSION

We were able to demonstrate an intensive rapid maturation between the second and sixth month of life with SPEM reaching an almost adult-like gain of 0.8 or higher. Further maturation is slow and not completed by 18 months. Stimulus velocity and size have an impact on the smooth pursuit quality. Discrepancies between our current results and those of previous studies may be explained partly by the widely differing stimulus properties. The influence of stimulus characteristics should be considered in smooth pursuit testing in infants.

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Competing interests None to declare.

Patient consent Obtained.

Ethics approval This study was conducted with the approval of the Ethics Committee of Kantonsspital St Gallen. The research followed the tenets of the Declaration of Helsinki.

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