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CLINICAL INVESTIGATION

Dora Lengyel
Silvia Weinacht
Jacques Charlier
Irene Gottlob

The development of visual pursuit during the first months of life

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D. Lengyel · S. Weinacht · I. Gottlob (✉)
Department of Strabismus
and Neuroophthalmology,
Kantonsspital St. Gallen,
CH-9007 St. Gallen,
Switzerland
Tel. +41-71-494 28 21;
fax +41-71-494 28 82;
e-mail ala2@ms1.kssg.ch

J. Charlier
Unité 279 INSERM, Lille, France

Abstract ● Background: There are few previous investigations of smooth pursuit in infants. The aim of our study was to quantify visual pursuit in infants between 1 day and 16 weeks of age. ● Methods: Eye movements of 97 healthy infants between 1 day and 16 weeks of age were recorded one to seven times with infrared photo-oculography. For stimulation of visual pursuit a square of 9.4 deg of visual angle with vertical gratings moved horizontally at a constant velocity of 7.5 deg/s. ● Results: In the first 2 weeks of life, segments of smooth pursuit were measured with a maximum velocity of 7.93 deg/s, with a maximum gain of 1.06 and a maximal duration of 3.16 s. In sequential recordings no significant increases of velocity, gain or duration were found. However, the total time the subjects followed the stimulus with smooth plus saccadic pursuit increased significantly with age (from a median of 39.0% to a median of 61.5% of examination time). ● Conclusion: This study clearly demonstrates that smooth pursuit is already present in the first week of life. We found no significant increase in velocity, gain and duration of smooth pursuit segments in the first 16 weeks of life with our recording technique. However, the total pursuit time, reflecting attention, increased with age. The ocular machinery to drive pursuit appears to be in place at birth and seems not to be influenced by increased attention in the first months of life.

Introduction

In the literature there are only a few quantitative studies investigating smooth pursuit in infants. It is not clear whether neonates can follow a target with smooth eye movements or whether they use only saccadic pursuit.

Kremenitzer et al. [8] reported the presence of brief segments of smooth eye movements in newborns and Roucoux et al. [11] in 4-week-old infants. For these studies a large target moving at a slow velocity was used. Jacobs et al. [7] observed an increase in smooth pursuit gain recorded by EOG during the first 7 months of life. Other studies with infrared recording techniques using smaller stimuli, however, showed a later onset of smooth pursuit. Aslin [2] reported that smooth pursuit starts at the age of 8 weeks. Shea and Aslin [12] found smooth pursuit at the age of 7 weeks. Up to that age pursuit was saccadic.

The purpose of this study was to investigate quantitatively pursuit in infants and to analyze its development in the first few months of life.

Methods

We examined 97 healthy infants (52 girls and 45 boys), born at gestational ages between 37 and 42 postmenstrual weeks (mean 40.2 weeks, SD 6.9 weeks), between the ages of 1 day and 112 days (mean 60.3 days). Infants were tested one to seven times (total of 329 sessions). Twenty-four examinations, performed on 17 infants, were not included in the data analysis, because the subjects were too irritable or sleepy. Therefore, the total number of examinations used for statistics was 305 performed on 97 infants. Twenty-six infants were examined once, 6 two times, 19 three times, 29 four times, 14 five times and 4 six times. At every session, an orthoptic examination was performed [grating acuity testing by preferential looking, ocular alignment (Hirschberg test), fusion (four-prism diopters base out test)] and pupillary reaction was measured. Children were examined in Prechtl's state III [10] (calm wakefulness with open eyes, regular breathing, absence of gross body movements), because more reliable results are obtained from infants in this behavioral state [4]. The examiner had the flexibility to spend sufficient time with each infant, so that a complete examination in Prechtl's state III was possible. The research followed the tenets of the declaration of Helsinki. Informed consent was obtained from the parents after the nature and possible consequences of the study were explained.

Eye movements were recorded under binocular conditions from the right eye with a photo-oculographic technique developed for examination of infants, based on the measurement of the relative position of the reflected image of an infrared source on the cornea and the pupil center [5]. This technique has the advantage that the measurements are absolute, without drift, which is quite suitable for the analysis of slow eye movements. The subject was seated in a reclined position in an infant car seat, the head placed between two soft cushions for lateral support, to avoid head movements, 30 cm from a cathode ray tube where stimuli for pursuit were generated. Infrared light (880 nm) was directed to the subject's right eye and the image of the eye was recorded by an infrared camera. Both infrared source and camera were placed over the infant's head. The infrared light was reflected by a hot mirror (dichroic filter separating visible light and infrared light) positioned in the center of the cathode ray tube. The reflected image of the eye movements was automatically analyzed and stored in a computer with a sampling frequency of 30 frames/s. The sampling frequency of 30 Hz was chosen for the following reasons. First, it reduces noise. Secondly, it is sufficiently high to detect possible saccades. A saccadic pursuit would clearly show a step on the recording and a back-to-back saccade can be easily detected, since the intersaccadic interval has a mean of 500 ms in infants [9]. For stimulation of visual pursuit, a square of 9.4 deg of visual angle with white and black vertical gratings [contrast 95%, mean luminance 5 cd/m^2, spatial frequencies of 0.1, 0.2, 0.4 or 0.8 cycles/deg (cpd)] moved horizontally at a constant velocity of 7.5 deg/s on the screen of the cathode ray tube with identical luminance, over a range of 56 deg.

To elicit attention, first a blinking black square was presented in the center of the screen. As soon as the infant fixated, the square with vertical gratings started to move horizontally to the right. After having reached the right margin of the screen the stimulus automatically started in the opposite direction, from the right to the left margin of the screen. When the stimulus reached the left margin of the screen it started moving again to the right, crossed for a third time the entire screen and finally stopped in the center after a total time of 38 s. In the first month of life the first stimulus used was 0.2 cpd. After 4 weeks of age the test was started with 0.4 or 0.8 cpd. If the infant followed, targets with higher spatial frequency were used. If there was no pursuit, targets with lower spatial frequency were used.

Calibration is defined by the geometry of the anterior chamber [3]. It was estimated from biometry data of eyes of subjects obtained at the same age as subjects used in our study. Sensitivity was 10 arcmin.

The slow phases were distinguished from the fast phases (saccades) by applying a velocity threshold of 40 deg/s for saccades. The average velocity of each slow phase was computed by linear regression over each data segment. The velocity gain was determined as the ratio between the average slow phase velocity and the velocity of the stimulus.

Since variation in subjects' attentiveness may lower the subjects' performance on pursuit, we selected the segment of smooth pursuit with the gain closest to 1 from all the recordings of one examination day for analysis. If there were several segments with the same optimal gain, the one with the longest duration of smooth pursuit was evaluated. In addition, the total pursuit time (saccadic plus smooth pursuit) was evaluated from the same recording.

Twenty-five subjects were examined with all four spatial frequencies (0.1, 0.2, 0.4 and 0.8 cpd) at one examination session.

For statistics, patients were grouped by 2-week intervals of age. Simple regression analysis and analysis of variance (ANOVA) with Scheffe *F*-test were used.

Results

We found a high correlation between grating acuity measured by preferential looking and pursuit eye movement (data not shown). Therefore, infants only followed the stimulus if they discriminated the spatial frequency used from the background. At the spatial frequency of 0.1 cpd the black bar and the white bar width each measured 4.7°; at 0.2 cpd, 2.4°; at 0.4 cpd, 1.2°; and for the highest spatial frequency (0.8 cpd), the width was 0.6°.

Figure 1 shows the age distribution for each spatial frequency at which the smooth pursuit was analyzed. A large proportion of our subjects under 1 month of age followed the stimuli with a bar width of 2.4° (0.2 cpd) or 1.2° (0.4 cpd). Since we found no relation between the spatial frequency of the stimulus and the gain or duration of smooth pursuit, we evaluated data independently of spatial frequency. The spatial frequency of the stimulus was 0.4 cpd in 39.0% of the segments that were analyzed, 0.8 cpd in 26.1%, 0.2 cpd in 18.7% and 0.1 cpd in 16.1%.

Examples of original recordings of the horizontal eye movements of three children are shown in Fig. 2. Figure 2A represents an example of the pursuit of a 5-day-old child at a stimulus with a spatial frequency of 0.2 cpd. The recording between the arrows corresponds to the segment selected as smooth pursuit (gain of 0.58, duration of 2.95 s). The child followed the stimulus for a total time of

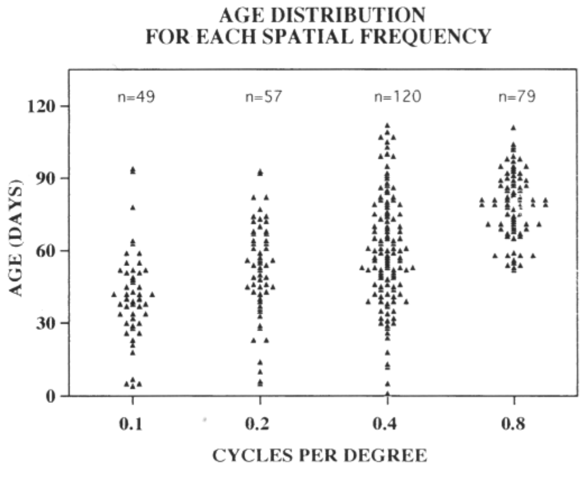

Fig. 1 Age distribution for each spatial frequency of 305 recordings

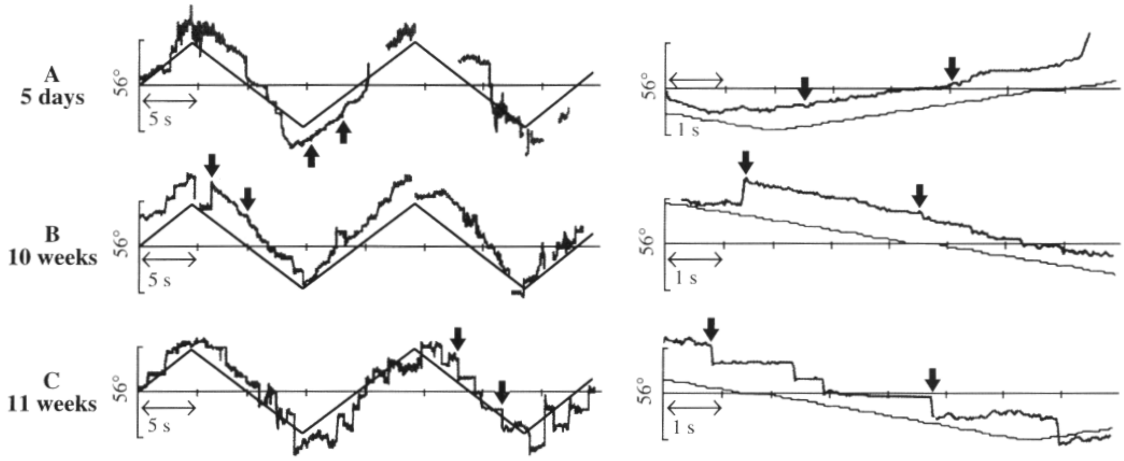

Fig. 2A–C Horizontal eye movement recordings of three subjects. *Upward directions* on tracings indicate eye movements to the right, *downward directions*, to the left. *Left column* Total recording time, *right column* detailed segment of recording (between arrows)

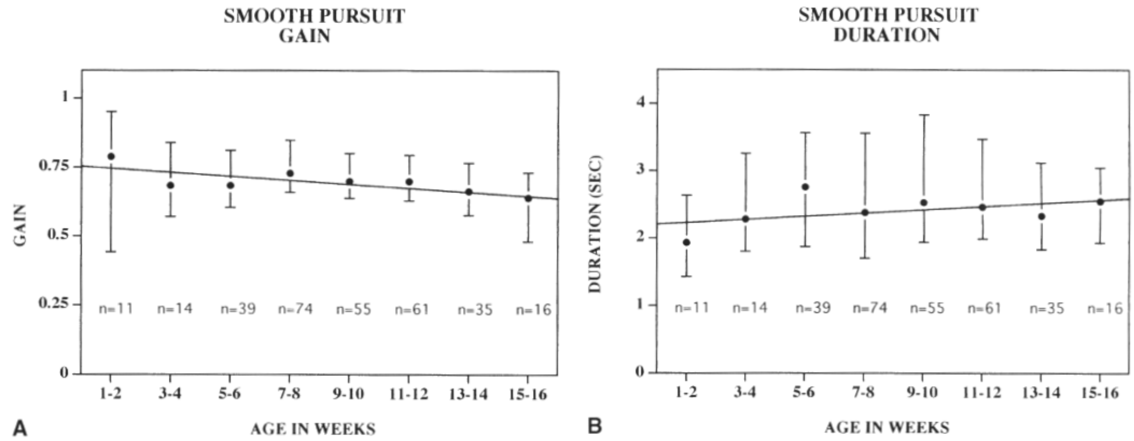

Fig. 3 Smooth pursuit gain (**A**) and duration (**B**) at constant target velocity of 7.5 deg/s of the different age groups, with regression line. Results are shown as medians; *vertical bars* indicate quartiles

29.0 s (sum of saccadic plus smooth pursuit segments). In Fig. 2B recordings of a 10-week-old infant at a stimulus with a spatial frequency of 0.8 cpd are shown. The segment of smooth pursuit between the arrows has about the same length (3.10 s) and gain (0.65) as in the recording of the 5-day-old infant (Fig. 2A). However, the total pursuit time is longer (36.5 s) in the 10-week-old infant. The majority of the children had segments of smooth pursuit in each recording. Rarely did an infant show only saccadic pursuit, as seen in Fig. 2C. This recording was performed at a stimulus of 0.4 cpd (total pursuit time of 38.0 s).

Figure 3A shows the gain for each of the eight age groups. In the first 2 weeks of life, smooth pursuit segments with a gain up to 1.06 (median 0.789) were measured. This corresponds to a maximal velocity of 7.93 deg/s (median 5.92 deg/s). In the next age groups up to the age of 15–16 weeks, the median gain ranged between 0.64 and 0.73.

There were no significant differences by simple regression or ANOVA between measurements at different ages. The quartiles did not decrease with age, suggesting that the precision of gain did not increase.

Figure 3B shows the duration of the smooth pursuit segments of the eight age groups. In the first 2 weeks of life the duration was up to 3.16 s (median 1.93 s). There appeared to be a trend towards an increase in duration of smooth pursuit segments in the first 6 weeks of

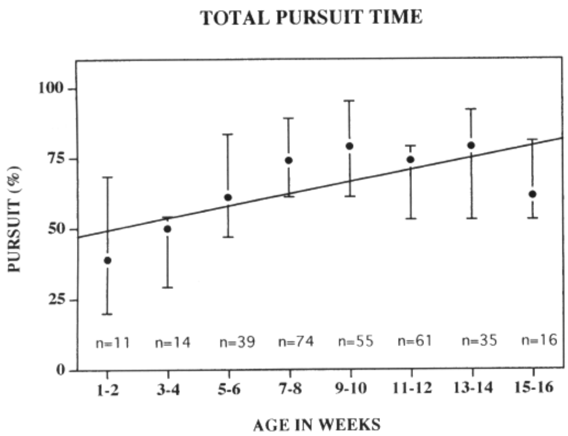

Fig. 4 Total time of pursuit (saccadic plus smooth) during the examinations of 38 s from 305 recordings with regression line. Results are shown as medians; *vertical bars* indicate quartiles

life. However, these changes were not statistically significant.

Figure 4 shows the total pursuit time (smooth plus saccadic pursuit) during which the subjects followed the stimulus in the selected best session of 38 s of examination time. In the first 2 weeks of life we recorded a maximum time of 30.0 s (79.0% of the total time of 38.0 s), with a median of 15.0 s (39.0%). At the age of 15–16 weeks the maximum pursuit time was 36 s (94.74%), with a median of 23.5 s (61.5%). The total pursuit time increased significantly with age ($P<0.005$). The analysis of variance showed a significant increase for age group 5 compared to age groups 1 ($P<0.05$) and 2 ($P<0.05$).

Discussion

These findings demonstrate that smooth pursuit is present in the first week of life. Interestingly, no statistically significant increase of gain and duration of smooth pursuit segments was found. However, the total pursuit time increased with age.

The early onset of smooth pursuit recorded by us with the infrared technique is in agreement with Kremenitzer et al. [8] and Roucoux et al. [11], who used the EOG. However, Aslin [2] and Shea and Aslin [12] found a later onset of smooth pursuit using the infrared technique. These differences may be due to differences in stimulation parameters, examination techniques and selection of subjects.

In the literature, different sizes of stimuli have been used. On the one hand, there are studies with larger stimuli, including that of Kremenitzer et al. [8] , who used a solid black circle subtending a visual angle of approximately 12° on a white background, and of Roucoux et al. [11] , whose target was a black-and-white "Mickey's head", subtending visual angles ranging from 10° to 2°. Using these stimuli, Kremenitzer et al. [8] detected smooth pursuit on the first day of life, and Roucoux et al. [11] for the youngest subjects in their study at the age of 4 weeks. On the other hand, there are studies with smaller targets, as used by Aslin [2] (a vertical black bar 2 deg wide and 8 deg high on a white background) and by Shea and Aslin [12] (2-deg white square on a black background). Aslin [2] identified the onset of smooth pursuit at 8 weeks of age (up to that age pursuit was only saccadic). In a subsequent study, Shea and Aslin [12] found smooth pursuit in the youngest subjects of the study, at 7 weeks of age. In our study, to follow the stimulus, the infant had to discriminate the stimulus against the background. The stimuli eliciting the best results in our study, had a bar width of 2.4 deg and 1.2 deg, therefore corresponding to the smaller stimuli used by Aslin [2] and Shea and Aslin [12] . However, in contrast to their studies, we demonstrated smooth pursuit in infants before 7 or 8 weeks of age using similar stimulus sizes.

Because small infants are more likely to follow a slow stimulus [2, 8, 11, 12] we used in our study a constant velocity of 7.5 deg/s. With this velocity we did not find an increase in the gain or duration of smooth pursuit. However, it is possible that faster velocities would show an improvement of smooth pursuit with age.

In this study we covered the whole age range of infants in whom smooth pursuit was reported in the literature in the first few months of life [2, 8, 11, 12]. Since previous studies have not covered this whole age range [2, 8, 11, 12] it can not be concluded from them that neonates have purely saccadic pursuit, and the kinetics of smooth pursuit development cannot be completely characterized.

In our study, we found no increase of smooth pursuit gain or duration during the first 16 weeks of age. It is unknown at what point the quality of smooth pursuit increases to reach that of adults. There may be a constant increase with age after 16 weeks or a sudden improvement, as seen for binocular visual function. Shupert and Fuchs [13] remark that it still remains unclear at what point during development smooth pursuit becomes adultlike over a wide range of target sizes and velocities. The next age group examined in the current literature is the primary school age. Accardo et al. [1] examined children of age 7–12 years using an infrared corneal reflection technique. Although, at this age, the smooth pursuit was much improved compared to the infants, a clear difference from smooth pursuit of adults was still found. In particular, gain is lower in children. Accardo et al. [1] conclude that these differences can be explained by psychological and cognitive factors and by incomplete maturation of the smooth pursuit system in children.

Hainline [6] attributed the presence or absence of smooth pursuit to the interest generated by the target.

Adults usually follow an object with smooth pursuit in order to inspect its fine details. If such inspection is not necessary, it requires less effort to observe the target using saccadic pursuit or a mixture of saccadic and smooth pursuit. In our study, the total time of pursuit (the addition of smooth and saccadic segments of one examination) increased significantly with age; therefore, the attention itself increased. Thus, the lack of increase in gain and duration of smooth pursuit with age cannot be attributed to decreasing attention to the stimulus. It is possible that more interesting stimuli with structures, like a face, would improve pursuit quality in infants as well.

In conclusion, we found smooth pursuit in the first week of life. We found no significant increase in velocity, gain and duration of smooth pursuit segments with our stimuli in the first 16 weeks of life. However, the total pursuit time, reflecting attention, increased with age. Therefore, the mechanisms involved in generating smooth pursuit appear to be present at birth and not to be influenced by increasing attention in the first few months of life.

To determine the maturation of smooth pursuit, further studies need to be performed with older children, with different stimuli and velocities.

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