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Development of visual pursuit in the first 6 years of life

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Abstract *Background:* There are few previous investigations on the development of smooth visual pursuit in children. The aim of this study was to determine normative values for the development of horizontal and vertical smooth pursuit in a large number of normal children. *Methods:* Eye movements of 358 healthy children aged 6 weeks through 6 years were recorded using infrared photo-oculography. Visual pursuit was elicited with colored squares of 1.2° of visual angle. The stimulus moved horizontally or vertically with constant velocities of 7.5, 15, or 30°/s. *Results:* Attention time increased with increasing age from 0.54 to 0.77 ($P<0.01$) and decreased with increasing stimulus velocities ($P<0.01$). The

ratio of time of smooth pursuit to time of smooth pursuit plus saccades increased with increasing age from 0.63 to 0.78 ($P<0.01$) and decreased with increasing stimulus velocities ($P<0.01$). For stimulus velocities of 7.5°/s, no significant difference was found between horizontal and vertical gain values. For stimulus velocities of 15°/s and 30°/s, gains for horizontal movements were larger than for vertical ($P<0.05$). Increasing stimulus speeds were associated with decreasing gains ($P<0.05$). *Conclusions:* This study provides the following normative values for photo-oculography in healthy children aged 6 weeks through 6 years of age: attention time, smooth pursuit time, and gain for three stimulus velocities presented horizontally and vertically. This normative database should help to diagnose pathologic ophthalmological or neuropediatric conditions, to perform screening interventions, and to initiate therapies.

Introduction

During visual tracking, visual axis are oriented by combining two different types of eye movements, smooth pursuit and saccades [8]. Smooth-pursuit is stimulated by a movement of an image upon the retina. The purpose of smooth pursuit is to stabilize moving objects on the retina thereby enabling us to perceive the object in detail. It cannot be induced voluntarily, but requires a moving object in the visual field. If the target is lost during sustained pursuit, catch-up saccades occur. Contrary to smooth pursuit, during saccades vision is suppressed since the perceived image quality would be highly deteriorated. Performance of

visual tracking varies considerably among individuals and is affected by many factors such as the properties of the stimulus, attention, and age. Visual pursuit represents a sensitive indicator of maturation of the visual system in humans [18]. The first investigations on development of visual pursuit were non-quantitative by observation alone [2–4, 15]. Later, these studies were followed by quantitative studies. However, the number of quantitative studies on visual pursuit development in children remains small [9, 10, 12, 13, 17]. In full-term infants, it has been shown that visual pursuit is present in the first week of life [11]. Several studies investigated the development of smooth pursuit during the first year of life and in primary school age [1, 2,

10, 11, 15]. However, visual pursuit has never been examined in a quantitative manner in a large number of children in the first years of life.

Therefore, the purpose of this study was to quantitatively investigate the development of horizontal and vertical pursuit in a large number of children in the first 6 years of life. This normative database should help to diagnose pathologic ophthalmological or neuropsychiatric conditions, to perform screening interventions, and to initiate therapies.

Materials and methods

This research followed the tenets of the Declaration of Helsinki and was approved by the Ethical Committee of Kantonsspital St Gallen. Informed consent was obtained from all parents after explanation of the nature and possible consequences of the study. An extensive description of the experimental setting has been published previously [5–7]. The stimulus generator and registration system was provided by Metrovision (Perenchies, France).

Subjects

Smooth pursuit eye movements were studied in 358 children up to the age of 6 years (197 girls and 161 boys). The average age was 2.72 ± 1.73 years. For gain calculations eight different age categories were chosen. The number of children available in each age category is mentioned in the according figure. All children were healthy and full-term. They were recruited in day-care centres and kindergarden. An orthoptic examination included Hirschberg ocular alignment test, cover test, four-prism diopter base out fusion test, and pupillary reaction. Additionally, in older children, visual acuity measurements and stereoscopic tests were performed. Children with abnormal findings were excluded from this study. Infants were examined in Prechtl's [14] state III (calm wakefulness with open eyes, regular breathing, absence of gross body movements), because more reliable results are obtained from infants in this behavioural state [6].

Methods

Stimulus presentation Infants and toddlers up to the age of 1.5 years were seated in a infant car seat (Maxicosy) with an inclination of 45° . This inclination minimizes pupil masquerade by the eyelid [7]. Their heads were not stabilized. Children between 1.5 and 6 years were seated on the lap of the mother or alone, with their heads stabilized by a chin and front rest. In both settings, the monitor for stimulus presentation was placed in a fronto-parallel position at a distance of 40 cm from the eyes.

Eye movement recordings Eye position was determined by measuring the position of the corneal reflex with respect to the center of the pupil. Eye movements were registered under binocular viewing conditions from the right eye. An infrared illumination of the eye (880 nm) was used to produce the corneal reflex and the pupil image. The system operated with a sampling rate of 30 Hz and achieved a resolution of 10 arc minutes [5]. Illumination source and camera were installed above the children's head. A hot mirror (dichroic filter separating visible light and infrared light) was used to illuminate the eye and to register the reflexes with a camera. Calibration is defined by the geometry of the anterior chamber [5]. It was estimated from biometry data of eyes of subjects obtained at the same age as subjects used in our study. Optimal alignment during registration was achieved looking at an image of the child's eye on a computer screen. If necessary, the head position of the child was adjusted during the registration period, either by adjusting the position of the camera or of the infant car seat by motor-driven mechanisms.

Stimulus characteristics Colored (red, violet, blue, yellow, white, green) $1.2^\circ \times 1.2^\circ$ squares with equal stimulus-background contrast were moving horizontally or vertically at a constant velocity of either $7.5^\circ/s$, $15^\circ/s$, or $30^\circ/s$ against a uniform gray background. Different colors were used in order to achieve a better attentiveness of the children. The colors changed randomly. The colors were all isoluminant. When the stimulus reached the edges of the screen a pause of 333 ms (square does not move) is implemented in the stimulus generating software to prevent the subjective impression that the stimulus moves faster when changing its direction. The stimulus amplitudes were 26.6° horizontally and 20.6° vertically. One test cycle (registration time) lasted 38 s. Each subject participated in every condition described.

Calibration Correction factors were derived from repeated presentations to a subpopulation of the study group of a vertical and horizontal step-ramp stimulus with the following coordinates (x/y=horizontal/vertical): left $10^\circ/0^\circ$, $0^\circ/0^\circ$, right $10^\circ/0^\circ$ and $0^\circ/\text{down } 10^\circ$, $0^\circ/0^\circ$, $0^\circ/\text{up } 10^\circ$.

Analysis of eye tracking movement data The exact statistical methods used to extrapolate missing values from blinking and to eliminate outliers have been described elsewhere in detail [16]. Loss by blinking was determined in normal subjects and found to be three measurements (0.1 s). Therefore, gaps of up to three data points were extrapolated for the x- and y-coordinates. Outliers were detected and eliminated using the robust mean and standard deviation. The amount of data representing non-optimal pursuing is considerable. For example, ideal optimal horizontal pursuit would consist in y-coordinates of only 0° . In order to determine which y-values (x-values) can be used for analysis of horizontal (vertical) eye movements, outliers are calculated by means of the median absolute

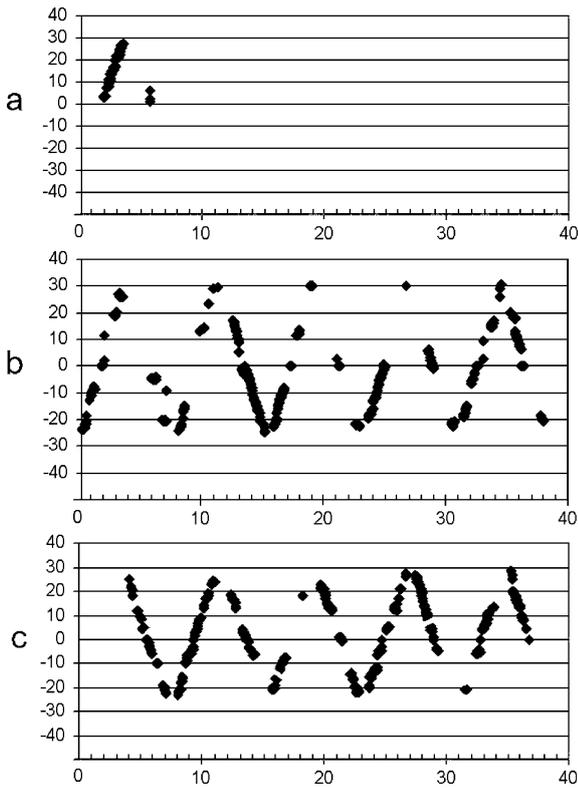


Fig. 1 Three examples of original recordings after automatic exclusion of outliers and detection of blinks. **a** A child of 1.5 years with poor cooperation, in which a recording time of only 7 s was possible. **b** Recording in a 3.5-year-old child with good cooperation. Excellent recording in a child of 6 years

deviation, a method from robust statistics [16]. The robust mean \bar{y} is given by the median of all values $y_i, i = 1, 2, \dots, n$:

$$\bar{y} = \text{median } y_i$$

and the robust standard deviation is determined by:

$$\sigma = 1.4826 \cdot \text{median} |y_i - \bar{y}|$$

Then, we only retain those y_i with $|y_i - \bar{y}| \leq \sigma$ for further consideration. In a similar manner x-values are filtered to determine those useful for analysis of vertical eye movements. For further details, we suggest the reading of our methodological article about the algorithm for data analysis from photo-oculography [16].

Calculation of tracking performance values The remaining data are used for calculation of the saccades and smooth pursuit. The slow phases are distinguished from the fast phases (saccades) by applying a velocity threshold of $40^\circ/\text{s}$ for saccades.[11] The velocity for each available pair of consecutive data points is determined by:

$$v = (x_2 - x_1)/(t_2 - t_1)$$

The relative attention time is calculated by dividing the attention time (smooth pursuit plus saccades) by the total

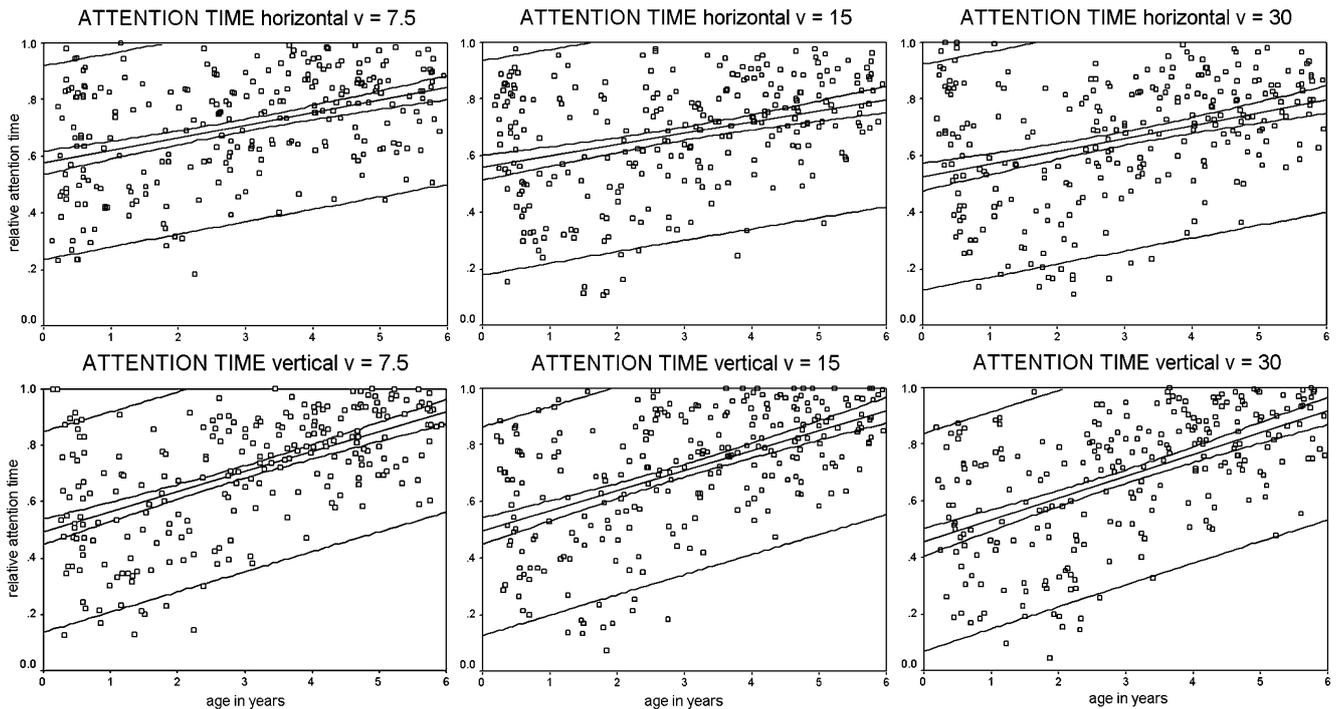


Fig. 2 Relative attention time for different stimulus directions and speeds

recording time. Relative saccadic time is 1-relative smooth pursuit time.

Statistical Analysis Data were analyzed using three different multiple linear regressions models with gain, relative attention time, and relative smooth pursuit as outcome parameters. Within subject explanatory variables were stimulus speed and stimulus plane (horizontal or vertical). Between subject explanatory variables were gender and age.

Results

The relative attention time, attention time divided by recording time, increased with increasing age from 0.54 to 0.77 ($P < 0.01$) and decreased with increasing stimulus velocities from 0.71 to 0.66 ($P < 0.01$). Figure 1 shows three examples of original recordings after automatic exclusion of outliers and detection of blinks. Figure 1a shows a child of 1.5 years with poor cooperation, in which a recording time of only 7 s was possible. Figure 1b depicts the recording in a 3.5 years child with good cooperation. Figure 1c shows an excellent recording in a child of 6 years. Figure 2 shows the normal values of relative attention time for horizontal and vertical stimuli of 7.5°/s, 15°/s, or

30°/s in function of age. Gender had no influence on attention time ($P > 0.1$). No significant interactions of explanatory variables were found.

The time of smooth pursuit relative to the time of smooth pursuit plus saccades increased with increasing age from 0.63 to 0.78 ($P < 0.01$) and decreased with increasing stimulus velocities from 0.66 to 0.59 ($P < 0.01$). Figure 3 shows the normal values of the percentage of smooth pursuit for horizontal and vertical stimuli of 7.5°/s, 15°/s, or 30°/s in function of age. Gender had no influence on relative pursuit time ($P > 0.1$). No significant interactions of explanatory variables were found.

Figure 4 shows smooth pursuit gain values for horizontal and vertical stimuli of 7.5°/s, 15°/s, or 30°/s in function of age and average values for all ages. Average gain over all ages was highest for horizontal pursuit of 7.5°/s (0.77) and lowest for vertical pursuit of 30°/s (0.33). For stimulus velocities of 7.5°/s, no significant difference was found between horizontal and vertical gain values (stimulus plane), if average gains for all ages were analyzed. For stimulus velocities of 15°/s and 30°/s, gains for horizontal movements were larger than for vertical ($P < 0.05$). Increasing stimulus speeds were associated with decreasing gains ($P < 0.05$). Gender had no influence on gain ($P > 0.1$). Speed interacted significantly with stimulus plane ($P < 0.01$).

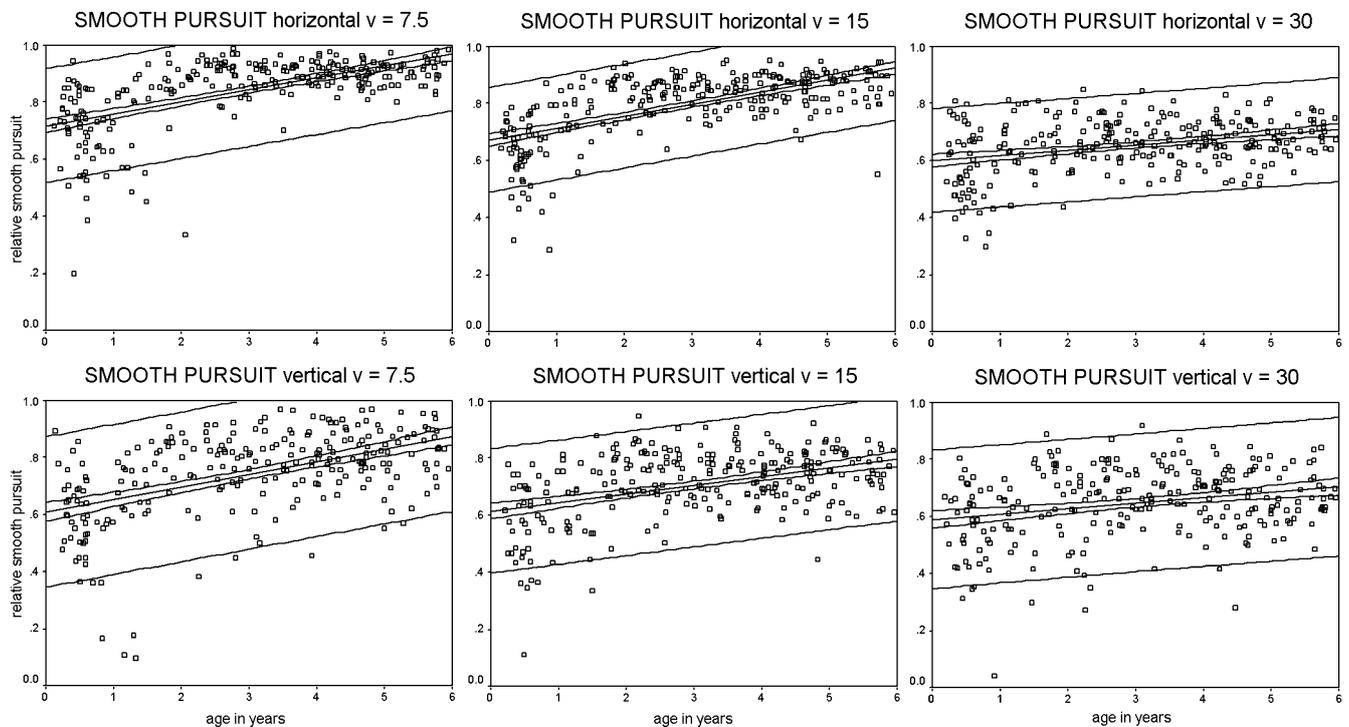


Fig. 3 Relative smooth pursuit time for different stimulus directions and speeds. Relative saccadic time would correspond to 1-relative smooth pursuit time

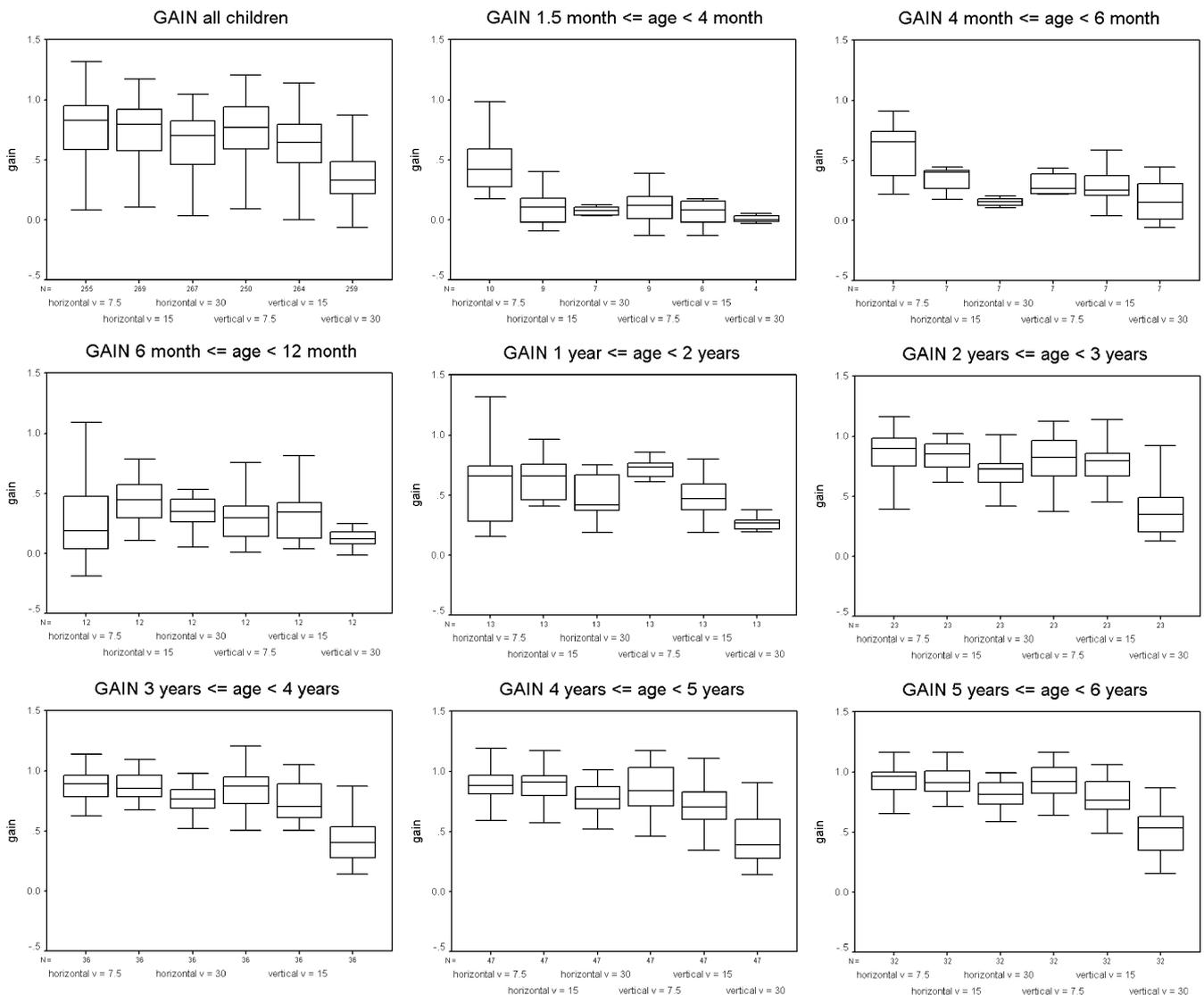


Fig. 4 Gain for different stimulus directions and speeds. The number for each category is mentioned directly below the figure (N)

Discussion

We studied the development of visual pursuit in the first 6 years of life in a large number of full-term, healthy children and found an increase in attention time, gain, and relative smooth pursuit with age. The very early phase of development has not been examined in this study since our youngest children were 6 weeks old. Others have studied the development during this very early phase of visual maturation [11].

This study provides the following normative values for photo-oculography in healthy children aged 6 weeks through 6 years of age: attention time, smooth pursuit time, and gain for stimulus velocities of $7.5^\circ/s$, $15^\circ/s$, and $30^\circ/s$ presented horizontally and vertically.

We found that an increasing age was associated with an increase in relative and absolute attention time. With in-

creasing stimulus velocities relative and absolute attention time decreased. Smooth pursuit time increased with increasing age and decreased with increasing stimulus velocities. Accordingly, saccadic time decreased with increasing age and increased with increasing stimulus velocities. The relative decrease of catch-up saccades with increasing age was associated, as expected, with an increase of gain. According to Accardo et al. [1], these findings can be explained by psychological and cognitive factors and by incomplete maturation of the smooth pursuit system in children.

In agreement with more recent studies, smooth pursuit is, at least in some babies, already present in the first 2 months of life [10, 11, 17].

Direct comparison of our values with other studies is only possible if similar registration techniques and stimuli have been used. Gain and smooth pursuit time of our children aged 6 weeks up to 4 months is in good agreement with

a previous study using similar stimuli and the same registration apparatus in children up to the age of 4 months [11].

In an ongoing study, we are determining in a large number of adults the influence of different parameters on visual pursuit. The actual available results show that children reach adult values at age 6 for most parameters and that horizontal visual pursuit remains better than the vertical one.

Comparison with other registration techniques has to be performed with caution. Two previous studies, one performed by Kowler and Martins [9] with two preschool children aged 4 years and 7 months and 5 years and 3 months and one by Phillips et al. [13] including 20 children aged 1–4 months found higher gains than we did. The comparison with the two children examined by Kowler and Martins is difficult, since these two children might have been more cooperative than average children of this age, or, because, just by chance, they were above the average in performing this task. A reason for the higher gains reported in the study of Phillips et al. could be due to the encouragement by vocalizations, squeaks and rattles between phases of target movement or because longer rests were allowed between registrations. Both groups used a bright point. Another reason for the slower gains could be due to

our use of squares to elicit visual pursuit. It could be possible that other stimuli, e.g. like a bright point or a face, would have improved the quality of smooth visual pursuit. Only similar registration conditions and stimuli will permit to compare future results with our findings. Since squares are easy to generate on a LCD screen and more complex stimuli, e.g. like faces, may lead to discussions which design would be best to elicit visual pursuit, we believe that the use of neutral squares will allow best comparison with future studies.

This normative database should be helpful to determine if visual pursuit in children is normal or not, and to find pathologic ophthalmological or neuropediatric conditions associated with abnormal visual pursuit. Possibly, it may show to be useful to perform screening interventions if used in combination with the registration of other parameters, e.g. like preferential looking or the development of random-dot stereopsis and to initiate therapies. However, care should be taken not only to use our normative database to determine abnormality by looking if a visual pursuit parameter is abnormally low. Better ways to determine abnormality have to include the examination of a large number of children with the specific abnormal condition and to study the overlap of all parameters, e.g. by calculating receiver operator characteristics.

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