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RESEARCH NOTE

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Smooth pursuit eye movements in children

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Abstract Smooth pursuit eye movements consists of slow eye movements that approximate the velocity of the eyes to that of a small moving target, so that target image is kept at or near the fovea. Little information on smooth pursuit is available in children. We used an infrared eye tracker to record smooth pursuit in 38 typically developing children, aged 8–19 years. Participants followed a visual target moving sinusoidally at $\pm 10°$ amplitude, horizontally and vertically at 0.25 or 0.5 Hz. The mean horizontal smooth pursuit gains, the ratio of eye to target velocities, were 0.84 at 0.25 Hz and 0.73 at 0.5 Hz. Mean vertical smooth pursuit gains were 0.68 at 0.25 Hz and 0.45 at 0.5 Hz. Smooth pursuit gains were significantly lower for vertical in comparison to horizontal tracking, and for 0.5 Hz in comparison to 0.25 Hz tracking ($P < 0.0001$). Smooth pursuit gains increased with age ($P < 0.01$, Pearson's correlation tests), with horizontal gains attaining reported adult values by mid adolescence. Vertical gains had large variability among participants. The median phase, the time interval between eye and target velocities, varied between 39 and 86 ms. Phase was not influenced by age. We conclude that smooth pursuit gains are lower in children than gains reported in adults. Vertical pursuit gain is significantly lower than horizontal pursuit gain. Gains improve with age and approach adult values in mid adolescence. Children have larger phases than reported adults values indicating that prediction in the smooth pursuit system is less mature in children.

Keywords Eye movements · Smooth pursuit · Children · Development

Introduction

Smooth pursuit eye movements consists of slow conjugate eye movements that stabilize the image of a slowly moving small target on or near the fovea and are required for high definition vision (Sharpe 1998; Leigh and Zee 1999). When smooth eye movements fail to approximate target speeds, saccades are used to attain foveation of targets.

Smooth pursuit eye movements are reliably identified by 2 months of age or earlier (Jacobs et al. 1997; Von Hofsten and Rosander 1997; Shea and Aslin 1990). At this age, tracking eye movements are mainly saccadic and actual smooth pursuit gain, defined as the ratio of smooth eye movement velocity to target velocity, is low (< 0.6) even for large targets moving as slowly as 10°/s (Jacobs et al. 1997). Smooth pursuit gain improves after 2 months of age, and becomes less saccadic (Jacobs et al. 1997). It is not clear when adult gain values are reached because only few studies have quantified smooth pursuit in children or adolescents. One study reported lower smooth pursuit gains in school-aged children, even at slow tracking velocities, than that reported in adults (Accardo et al. 1995). We hypothesized that smooth pursuit tracking is immature in young children especially at higher tracking velocities and that smooth pursuit improves with age during childhood as the brain

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matures. We also hypothesized that horizontal eye tracking is better developed that vertical eye tracking, because daily human activities involve horizontal more than vertical eye movements, for example saccades during reading.

Methods

Participants

Thirty-eight typically developing children (21 males) between 8 and 19 years of age (mean 13.8, SD 3.4) were recruited by local advertising. The study was in accord with the declaration of Helsinki guidelines. Ethical approval for this project was obtained from the Research Ethics Boards of the Hospital for Sick Children and the University Health Network. Written consent and assent were obtained from the participants and their legal guardians. Participants with best corrected, monocular visual acuity of at least 20/40 were selected and excluded if they had any illness or were on medication.

Equipment and procedures

We recorded smooth pursuit with the El Mar eye tracker (El-Mar Inc., Downsview, ON, Canada), an infrared video eye tracking system (DiScenna et al. 1995). The video image is sampled at 120 Hz. The system accuracy is 0.5° while its resolution is 0.1° with a linear visual range up to ±40° horizontally and ±30° vertically.

Each participant was seated with the eyes in the primary position, facing the center of a 45 cm computer monitor (Samsung, SyncMaster 900 NF) that was located 57 cm from the participant's cornea. The participant's head was stabilized using a chin rest. Participants were instructed to keep their heads steady. The visual target displayed on the computer monitor, was a 2-mm, white square light that subtended 12 min of arc. Stimulus luminance was 65 cd/m^2. The background monitor luminance was 0.01 cd/m^2. The laboratory was dimly lit. Positions of each eye were calibrated with the fellow eye occluded at 14 horizontal and vertical fixation light points. Participants' performance, head movements and alertness were monitored by TV and by an oscilloscope display of horizontal and vertical eye movements.

The non-preferred eye was covered with an eye patch and movements of the viewing eye were measured. The target moved smoothly and sinusoidally, with ±10° amplitude horizontally (right and left), and then vertically (up and down from mid position) after a 30 s break. An initial fixation period of 2 s was followed by twenty cycles at 0.25 and then 0.5 Hz frequencies, yielding peak target velocities (peak acceleration) of 15.5°/s (24.7°/s^2) and 31°/s (98.7°/s^2) respectively.

Analyses

Target, head, and eye movement data were digitized for off-line analysis. Saccades, defined as fast eye movements with a minimum velocity of 60°/s, were automatically marked by purpose-designed computer software, when eye velocity exceeded 30°/s. Data were displayed on a computer monitor so that computer automated markings could be edited.

Eye position traces were created after removing the marked saccades or artifacts and replacing the missing segments with an interpolated parabola. Target and eye position traces were then differentiated with a maximally flat low-pass digital filter (finite impulse response-28 point filter, 24 Hz bandwidth, linear phase, Selesnick 2002). Each cycle of the resultant eye velocity trace was then fitted with a sinusoidal function, using the least squares harmonic analysis method to determine the amplitude and phase of the response for a given frequency (Sokolnikoff and Sokolnikoff 1941). The fitted sinusoidal cycles were visually inspected in relationship to the data points and appraised for goodness of the sine fit. Graphic displays of the residuals were also plotted. The fitted sine function was accepted when the distribution of the residuals was random and their values were small.

Smooth pursuit gain for each cycle was calculated as the ratio of the amplitude of the fitted sine function of the eye velocity trace to the amplitude of the sine function of target velocity trace, while smooth pursuit phase was the temporal difference (in degrees) between the eye and target velocity traces. This method, therefore utilizes most of the eye motion data.

For each participant, the means and SDs of smooth pursuit gains and phases, for each target direction and frequency were calculated. Analyses were performed using SPSS (Version 11, 2001). Normality of data distribution was tested using the mean, median, SD, skewness, kurtosis, and box plots. Paired Student's *t* tests or the Wilcoxon signed ranks test were used to analyze the data. Smooth pursuit parameters were correlated with age using Pearson correlation test. Difference in smooth pursuit gains based on gender was investigated using independent two-tailed, Student's *t* tests (Altman 1995). Bonferroni correction was applied for multiple comparisons. $P < 0.025$ was considered significant.

Results

Smooth pursuit gains but not phases had approximately normal distribution. Mean horizontal smooth pursuit gains were 0.84 at 0.25 Hz and 0.73 at 0.5 Hz. Mean vertical smooth pursuit gains were 0.68 at 0.25 Hz and 0.45 at 0.5 Hz (Table 1). When smooth pursuit gains were compared by target direction and frequency, there were significant differences in mean

Table 1 Smooth pursuit (SP) gains (±1 SD) and phases in degrees (range) by target frequency and direction

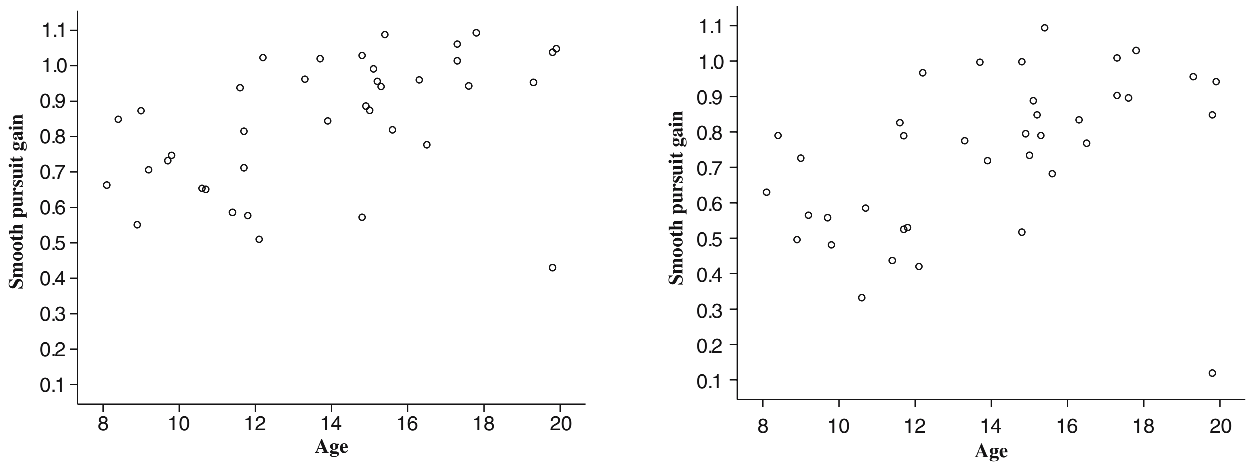
	Horizontal SP at 0.25 Hz	Vertical SP at 0.25 Hz	Horizontal SP at 0.5 Hz	Vertical SP at 0.5 Hz
Mean number of cycles	15 (3)	14 (3)	14 (4)	11 (3)
Mean gain	0.84 (0.18)	0.68 (0.23)	0.73 (0.22)	0.45 (0.2)
Median phase	−6.5 (−11.2 to 4.7)	−3.5 (−18.3 to 10.9)	−15.5 (−30.5 to −4)	−9.5 (−30.3 to 16.2)

smooth pursuit gains between the two frequencies for both horizontal ($P < 0.0001$) or vertical ($P < 0.0001$) target directions. In addition, there were significant differences in smooth pursuit gains when horizontal versus vertical directions were compared at each of the two target frequencies ($P < 0.0001$). There was a phase (time) lag between the eye and target velocity traces. Median (mean) horizontal smooth pursuit phases were −6.5° (−6.1°) at 0.25 Hz and −15.5° (−16.8°) at 0.5 Hz. Median (mean) vertical smooth pursuit phases were −3.5° (−3.6°) at 0.25 Hz and −9.5° (−10.9°) at 0.5 Hz. Maximum median phase lag of 15.5° represents a delay of the eyes behind the target of 86 ms (delay in ms = phase shift in degrees/[frequency × 0.36]). Smooth pursuit phases were also significantly different by target direction ($P = 0.005$) and frequency ($P < 0.0001$) (Table 1).

Mean smooth pursuit gains but not phases increased significantly with age for horizontal target movement, with a similar trend for vertical target movement

a) Horizontal target motion at 0.25 Hz. r =0.46, p = 0.004

b) Horizontal target motion at 0.5 Hz. r =0.41, p = 0.012



c) Vertical target motion at 0.25 Hz. r =0.31, p = 0.055

d) Vertical target motion at 0.5 Hz. r =0.31, p = 0.060

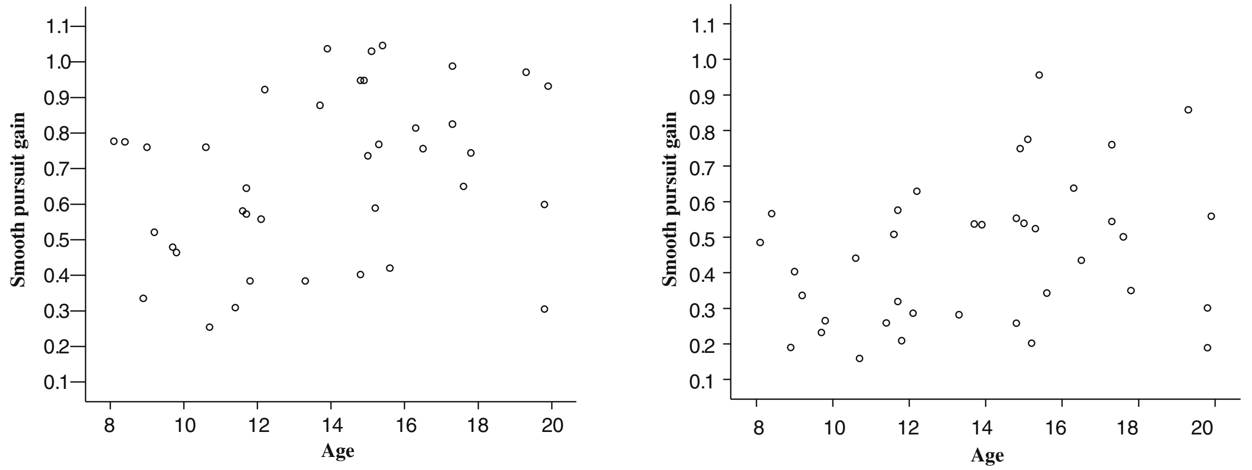


Fig. 1 Scatter plots of mean smooth pursuit (SP) gain of each participant and age in years by target frequency and direction. Gain increases with age. *r* is Pearson correlation coefficient

(Fig. 1). There was no significant difference in mean smooth pursuit gains between males and females.

Discussion

Horizontal smooth pursuit gains in mid adolescence were in the same range as values reported in adult studies (Schalén 1980; Zackon and Sharpe 1987). Vertical smooth pursuit gains were lower than horizontal gains and varied widely among participants, with less clear developmental changes, reflecting perhaps the lesser importance of vertical tracking in everyday human behavior. This finding has also been reported in adults (Leigh and Zee 1999; Kim and Sharpe 2001), suggesting that it is not related to developmental maturation. Fatigue is an unlikely explanation since participants rested between the horizontal and vertical tasks. Increasing target frequency lowers smooth pursuit gain in children as described previously in adults (Zackon and Sharpe 1987; Haishi and Kokubun 1995; Kim and Sharpe 2001).

There are conflicting reports with regard to the age at which the smooth pursuit system matures. One study (Katsanis 1998) used an infrared eye tracker to measure smooth pursuit of a sinusoidally moving target in 137 participants aged 11–12 years, 17–18 years, and adults. Horizontal smooth pursuit gains were reported to reach adult values at 17–18 years. In contrast, another study reported horizontal smooth pursuit gain of 0.97 in 32 children, aged 5–7 years when they tracked a sinusoidally moving target at 0.3 Hz frequency using an infrared eye tracker (Langaas 1998).

However, many studies report lower smooth pursuit gain in children in comparison to adults. Using a similar design to the one in our study, Accardo et al. (1995) reported horizontal smooth pursuit gains of 0.83 in 10 children aged 7–12 years and 0.95 in 10 adults at 0.4 Hz target frequency. Ross et al. (1993), reported horizontal smooth pursuit gain of 0.88 in 53 school-age children for a target moving at a constant velocity of 12°/s, using an infrared eye tracker. Gain increased with age. Similar smooth pursuit gain values for children have been reported in other studies (e.g. Jacobsen et al. 1996).

The improvement in smooth pursuit gains with increasing age reflects ongoing brain development in children. Lower smooth pursuit gains in children may reflect the immaturity of several processes that occur during computation of the target and eye movement velocities which involves translation from sensory to motor coordinates, speed of sensory processing of motion, motivation, or attention (Shea and Aslin 1990; Jacobs et al. 1997). Developmental maturation is related to brain myelination, which progresses from dorsal to ventral brain regions. Frontal, temporal, and posterior parietal cortices, which are involved in smooth pursuit processing (Sharpe 1998; Leigh and Zee 1999), continue to acquire myelin throughout childhood and early adulthood (Barkovich 2000).

Sinusoidal target movements are predictable. Phase lag is close to zero with predictable target movements and increases with increasing target frequency in adults (Ohashi, 1987; Morrow and Sharpe 1990). This is in agreement with our results. Morrow and Sharpe (1990) reported a mean phase lag of the eyes behind the target of 48 ms in 12 adults tracking at a target frequency of 2 Hz. This represents a smaller phase lag at a faster target frequency, than that used in our investigation. Prediction in the smooth pursuit system in children therefore, seems to be less mature than in adults. The current study also revealed that tracking direction influences the magnitude of smooth pursuit phase. The reason for the smaller vertical phase lag in comparison to the horizontal phase lag is not clear.

One study reported age-related phase difference among 28 children, aged 3–6 years tracking a horizontal target moving sinusoidally at 0.3, 0.5, 0.7 Hz using EOG (Haishi and Kokubun 1995). This contrasted with our results and may be related to our older subjects or the method of recording eye movements. In addition, the phase lag in our participants is larger than that reported previously in children (Accardo et al. 1995; Haishi and Kokubun 1995), and may be related to the eye tracker sampling frequency. The absolute values of smooth pursuit phases are limited by the eye tracker's sampling rate. Such errors have been estimated to be about 17 ms.

Recording eye movements in children remains difficult and challenging. Our study adds important information to the sparse knowledge that is available in this area of research in children. The use of a non-invasive and well-tolerated eye tracker in a relatively large number of children demonstrates its potential for investigation of the maturation of the pursuit system and its impairment by brain disease in children.

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