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# Saccades in children

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**Abstract**

Saccades are necessary for optimal vision. Little is known about saccades in children. We recorded saccades using an infrared eye tracker in 39 children, aged 8–19 years. Participants made saccades to visual targets that stepped 10° or 15° horizontally and 5° or 10° vertically at unpredictable time intervals. Saccadic latency decreased significantly with increasing age, while saccadic gain and peak velocity did not vary with age. Saccadic gains and peak velocities in children are similar to reported adult values. This implies maturity of the neural circuits responsible for making saccades accurate and fast. Saccade latency decreases as the brain matures.


*Keywords:* Saccade; Children; Tracking

## 1. Introduction

Visually guided saccades are rapid eye movements that position a target of interest on the fovea for high definition vision (Leigh & Zee, 1999). Saccades are important for many cognitive processes, such as reading and visual search (Liversedge & Findlay, 2000).

Different parameters are used to characterize saccades. Saccadic amplitude gain, the ratio of saccade amplitude to target amplitude, approaches unity for medium size saccades (i.e., 10–20°) in adults (Collewijn, Erkelens, & Steinman, 1988a; Sharpe & Zackon, 1987). In young infants, saccadic gain can be as low as 0.5 (Aslin & Salapatek, 1975). Indeed, it may take young infants 3–4 saccades to foveate a visual target (Aslin & Salapatek, 1975; Jacobs, Harris, Shawkat, & Taylor, 1992; Leigh & Zee, 1999). By one year of age, saccadic gain improves substantially and may approach adult values. Saccadic peak velocities have been reported to be higher in children than in adults (Accardo, Pensiero, Da Pozzo, & Perissutti, 1992; Fioravanti, Inchingolo, Pensiero, & Spanio, 1995), though this is controversial (Babu et al., 2003). Saccadic latency, the time from target displacement to response initiation, is the time period taken for a saccade to be programmed and dispatched. It is around 180–220 ms in adults, or shorter with predictable saccades (Gagnon, O'Driscoll, Petrides, & Pike, 2002; Walker, Walker, Husain, & Kennard, 2000). Infants have longer saccadic latencies of about

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500 ms (Aslin & Salapatek, 1975), which decrease with increasing age (Fukushima, Hatta, & Fukushima, 2000; Kapoula & Bucci, 2002).

Ocular motor research in children is challenging. We found only a limited number of studies on saccades in children. These studies mostly had a handful of participants with a narrow age range and uneven gender distribution. Many used EOG with its inherent disadvantages. The developmental profiles of saccadic gains, peak velocities, and latencies have not been quantified systematically using more modern eye trackers. In addition, although some saccadic parameters have been reported to reach adult values in the second half of the first decade or during adolescence (Aslin & Salapatek, 1975; Babu et al., 2003), this has not been clearly established with many studies reporting conflicting results (Accardo et al., 1992; Babu et al., 2003; Fioravanti et al., 1995; Fukushima et al., 2000). Furthermore, studies on the characteristics of vertical saccades in children are lacking.

We investigated saccadic accuracy, peak velocities, and latencies in response to horizontal and vertical target steps in 39 typically developing children and young adolescents. We hypothesized that saccadic parameters would show variation with age during childhood.

By the end of the first decade, the brainstem and cerebellum are well developed and myelinated, while the cerebral hemispheres continue to myelinate throughout childhood and continue beyond adolescence (Barkovich, 2000). The saccadic neural network that is responsible for making saccades fast and accurate is primarily located in the brainstem and cerebellum. For example, saccadic burst cells and ocular motor neurons, whose discharge rate encode saccade velocity, are located in the brainstem (Leigh & Zee, 1999); while saccade-related Purkinje cells in the ocular motor vermis and neurons in the caudal part of the fastigial nuclei in the cerebellum (Leigh & Zee, 1999), regulate saccadic amplitude through their discharge rate and pattern. Programming saccades, which reflect saccadic latency, however, involve in addition other parts of the saccadic neural network, for example, the parietal and frontal lobes (Sharpe & Zackon, 1987). We predicted that saccadic accuracy and peak velocity approaches adult values at an earlier age than saccadic latency in children, reflecting the different times at which parts of the saccadic neural network matures. It is difficult to predict the precise age however, because little information is available about the different components of the saccadic neural network in children and specifically, the contribution that each structure makes for processing saccades. It may not mirror what we know about saccadic processing in adults. In addition, other factors may be important, for example, attention, which influences saccades (Cohen & Ross, 1978; Leigh & Zee, 1999) and improves with increasing age of the child (Ross, Radant, Young, & Hommer, 1994).

Most daily activities in humans involve making horizontal saccades, for example, reading (Liversedge & Findlay, 2000). Therefore, we predicted that horizontal saccades would be more accurate, faster, and have shorter latency than vertical saccades.

## 2. Methods

### 2.1. Participants

Thirty-nine typically developing children (21 males) between 8 and 19 years of age (mean age 13.7 years, SD 3.5 years) were recruited by local advertising. The study was in accord with the declaration of Helsinki guidelines and ethical approval for this project was obtained from the Research Ethics Board at the Hospital for Sick Children and the University Health Network, Toronto. Written consent and assent were obtained from the participants and their legal guardians. Participants with best corrected monocular visual acuity of 20/40 were selected and excluded if they had impaired intelligence or ocular, neurological, and psychiatric disorders, or were on medication with drugs that might interfere with eye movements (e.g., sedatives or anticonvulsant medication).

### 2.2. Equipment and procedure

#### 2.2.1. Eye tracker

We recorded saccades with the El Mar eye tracker (El-Mar, Downsview, Ont., Canada), an infrared video eye tracking system that determines the horizontal and vertical eye position from the relative positions of multiple corneal reflections and center of pupil (Allison, Eizenman, & Cheung, 1996; Allison, Eizenman, Tomlinson, Nedzelski, & Sharpe, 1997; DiScenna, Das, Zivotofsky, Seidman, & Leigh, 1995). The optical components are mounted on a lightweight spectacle frame which weighed ~300 g. The video image is sampled at 120 Hz. The system accuracy is 0.5° with a linear visual range of ±40° horizontally and ±30° vertically. The system is free from drift and has a resolution (i.e., minimum detectable movement) of 0.1°. Horizontal and vertical head movements were recorded using a magnetic head tracker (Flock of Birds™, Ascension Technology Corp., Burlington, VT).

Each participant was seated with his or her eyes in the central position, facing the center of a 45 cm computer monitor (Samsung, SyncMaster 900 NF), located 57 cm from the participant's cornea. The participant's head was stabilized using a chin rest. The visual target displayed on the computer monitor, was a 2-mm, white square light that subtended 12 arc min. Stimulus luminance was 65 cd/m$^2$. The background monitor luminance was 0.01 cd/m$^2$. The laboratory was lit dimly.

Participants' performance and alertness were monitored by TV and by an oscilloscope display of horizontal and vertical eye movements to provide feedback during the task.

*2.2.2. Calibration*

Positions of each eye were calibrated with the fellow eye occluded at 14 fixation light points, arrayed along the horizontal (seven fixation points) and vertical (seven fixation points) axes and separated by 3.3° visual angle. The participant's head was stabilized using a chin rest and adjusted so that the eyes were in the central position when looking at the center of the array. Eyeglasses were removed prior to testing because they interfere with the function of the eye tracker. The uncorrected visual acuity in all cases was adequate for seeing and responding to the stimuli.

*2.2.3. Task*

An eye patch was used to cover the non-preferred (non-sighting) eye (Mapp, Ono, & Barbeito, 2003) in all participants. Movements of the viewing eye were measured. The target stepped between the center of the computer monitor and points located ±10° or ±15° horizontally and ±5° or ±10° vertically. These steps were chosen to test the working range that most people use for saccades. We also wanted to avoid large-amplitude saccades, because large-amplitude saccades are associated with head movements, which we wanted to avoid. Twenty target steps were presented at each amplitude and direction. The off-center locations and directions were presented randomly. Each trial started with the target on for at least one second before it stepped to the next location after a random interval between 0 and 0.5 s. Therefore, predictive saccades, which would confound measurements of saccade latency, were minimized (Gagnon et al., 2002; Ross & Ross, 1987).

## 2.3. Processing of the eye movement data

The stimulus, head, and eye movements were digitized for off-line analysis. Stimulus, head, and eye velocity data were filtered using a 5-point Savitsky-Golay differentiator (Savitsky & Golay, 1964). This is a high bandwidth differentiator that is used for determining saccade velocities. It was used because it does not attenuate the peak velocity and provides some noise immunity. It is described as follows: velocity $(j) = 8.0 * (\mathrm{pos}(j+1) - \mathrm{pos}(j-1)) - (\mathrm{pos}(j+2) - \mathrm{pos}(j-2))/(\mathrm{dt} * 12.0)$ where $j$ is the index of a sample, pos is a position sample, and dt is delta time in seconds.

Initial saccades were included in the analyses if they had a minimum velocity of 100°/s, were in the same direction as the target displacement, if the eye position trace shifted <0.5° from baseline during the 200 ms prior to target displacement up to saccade onset, and if saccades occurred within a latency of 70–450 ms to insure that only visually directed non-anticipatory saccades were included. The beginning and end of saccades were marked automatically by computer software when eye velocity reached 30°/s. Each second of data was displayed on a computer monitor so that the automatic markings could be verified by inspection.

Mean horizontal or vertical head position was checked for each participant before, during, and after saccades to ensure that no head rotation $\geqslant 0.5°$, induced the vestibulo-ocular reflex or changed the size of the required saccade. None of the saccades was associated with horizontal or vertical head rotation $\geqslant 0.5°$.

## 2.4. Analyses

For each participant, we calculated the means and SD of the initial saccadic amplitude gains, defined as the ratio of the first saccade amplitude to target amplitude and latencies. Saccade latencies were measured as the time between target step and the beginning of saccades, detected at the point when the eye velocity reached 30°/s. Saccadic peak velocity (PV)-amplitude ($A$) relationship, known as the *main sequence* (Bahill, Clark, & Stark, 1975), was computed for each direction from scatter plots of individual saccades that were fitted to an exponential curve: $\mathrm{PV} = V\,[1 - \exp\,(-A/C)]$ for each participant, where $V$ is the maximum velocity at the asymptote of the curve and $C$ is a constant. This exponential equation served to best fit the non-linear relationship relating saccadic amplitude to peak velocity (Lewis, Kline, & Sharpe, 1996; Sharpe & Zackon, 1987).

Analyses were done using a Statistical Package for Social Sciences (SPSS, 2001). Normality of data distribution was tested using the mean, median, SD, skewness, kurtosis, box plots, normal Q–Q plots, and Shapiro–Wilk test.

Saccadic parameters were compared by direction using the paired Student $t$-test for normally distributed data or the Wilcoxon signed rank test for non-parametric data. Saccadic parameters means across multiple target amplitudes were compared using Friedman test. Saccadic parameters were correlated with age to investigate the strength of the association between these variables using Pearson correlation test for normally distributed data or Spearman correlation rank test for non-parametric data. Differences in saccadic parameters based on gender were investigated using independent two-tailed, Student $t$-tests. Stepwise linear regression analyses were used to describe the effect of age and gender on saccadic gains or latencies as the dependent variables.

The Bonferroni adjustment was applied because multiple comparisons, which comprised of seven combinations of saccadic directions, amplitude gains, peak velocities, and latencies (totaling 18), are more likely to yield significant results (type I, false positive errors). However, a conservative 5 rather than 18 adjustments were chosen to avoid over-adjustment for the following reasons: saccadic parameters are not independent variables because there is a relationship between saccadic amplitude and latency, and between saccadic amplitude and peak velocity. In addition, the size of the target steps affects saccadic gains, for example, saccadic gain to 5° and 10° saccades are not independent. A $p$ value $<0.01$ was chosen as the level required to achieve statistical significance (Miller, 1981; Altman, 1995).

### 2.5. Validity of inclusion and exclusion of saccadic measurements

Horizontal saccades to 15° target steps in the nasal field were analyzed, but temporally directed saccades to 15° target steps were excluded because of the blind spot. Leftward 15° saccades were made by the viewing right eye in 31 participants, and rightward 15° saccades were made by the viewing left eye in 8 participants. There was no significant difference in these nasally directed 15° saccade amplitude gains when right and left eye saccade gains were compared using Student $t$-test.

The number of saccades for each target direction and amplitude varied among participants. This gave the data for saccadic gains and latencies from each participant a different 'weight'. For example, some participants made 12 saccades to a 10° horizontal steps, while others made 18 saccades to 10° horizontal steps. Variability in the number of saccades may have arisen from stringent inclusion criteria for each saccade, anticipatory saccades, blinks, and noisy or unstable eye tracker signal.

Variability in the number of saccades could confound analyses. To overcome this variation, a statistical formula ($N = 4 \times (\mathrm{SD})^2/L^2$) was used in which the minimum number of saccades ($N$) was calculated for different precision (errors in mean) values ($L$), using the standard deviation (SD) of the group saccadic gain (Snedecor & Cochran, 1980). This formula allows, with 95% confidence, for an error around the mean that will not exceed $L$. $N$ represented the minimum number of saccades for a particular target direction and amplitude that each participant had to have before his or her results could be included in saccadic gain and latency analyses. The statistical formula assumes that the mean gain and SD among the participants were similar to the mean and SD of saccades in each participant. Therefore, the group mean gain and SD *for each saccade direction and amplitude* was used to calculate $N$, using different precision (error) values ranging from 5% to 13%. A suitable cut-off point for $N$ was then chosen for each target direction and amplitude based on a suitable trade-off, where the precision value (error) was kept to a minimum without threatening the validity of the study caused by excluding participants. The cut-off values that were chosen for the minimum number of saccades varied between 7 and 11 for precision values of 6% for all horizontal target steps and 10% for all vertical target steps, except for saccades made to 10° upward target steps, which yielded larger variability in saccade amplitude; a larger error of 13% was tolerated to avoid excluding too many participants.

If participants contributed fewer saccades than the cut-off value for $N$ for a particular target direction and amplitude, then their contribution for that particular target amplitude and direction was excluded from saccadic gain and latency analyses.

## 3. Results

Saccadic gains, peak velocities, and latencies of the group had approximately normal distribution. Gains for leftward 10° target step and asymptotic peak velocity for leftward saccades for the group were slightly skewed and had a long-tail Gaussian distribution. Mean saccadic gains, latencies, and asymptotic peak velocities are shown in Tables 1 and 2, and Figs. 1 and 2. Mean saccadic gain to 15° nasal target steps was 0.96, mean latency was 258 ms, and mean asymptotic peak velocity was 521°/s. Mean saccadic gain was lowest (0.9) for 10° downward target steps (Fig. 2A). However, mean saccadic gains were not significantly different across target steps of varying amplitudes ($p = 0.382$). Mean saccadic latency to 5° downward target steps was significantly longer ($p < 0.0001$) than latencies to other target steps (Fig. 2B). Asymptotic peak velocities were not significantly different between upward versus downward

Table 1
Mean saccadic latencies (ms) and gains (SD) by target amplitude and direction

| | Number of participants | Mean number of saccades | Mean latency | Mean gain |
|---|---|---|---|---|
| Nasal 15° | 34 | 13.1 (2.8) | 257.6 (29.1) | 0.96 (0.08) |
| Rightward 10° | 39 | 15.8 (3.0) | 248.7 (20.5) | 0.96 (0.08) |
| Leftward 10° | 39 | 15.1 (2.7) | 253.6 (27.4) | 0.96 (0.08) |
| Upward 10° | 33 | 12.5 (2.5) | 243.3 (29.4) | 0.93 (0.15) |
| Downward 10° | 34 | 14.2 (2.5) | 247.0 (24.2) | 0.90 (0.16) |
| Upward 5° | 36 | 17.4 (3.1) | 240.3 (22.6) | 0.95 (0.15) |
| Downward 5° | 37 | 17.8 (3.2) | 268.3 (23.5) | 0.96 (0.16) |

Table 2
Mean asymptotic peak velocities (°/s, SD)

| | Mean number of saccades[a] | Mean asymptotic peak velocity |
|---|---|---|
| Rightward saccades | 26 (7) | 521.2 (90.7) |
| Leftward saccades | 26 (6) | 537.4 (83.6) |
| Upward saccades | 30 (7) | 466.9 (117.5) |
| Downward saccades | 28 (6) | 435.7 (111.5) |

All saccades that met the inclusion criteria are included.
[a] Data from all 39 participants are shown.

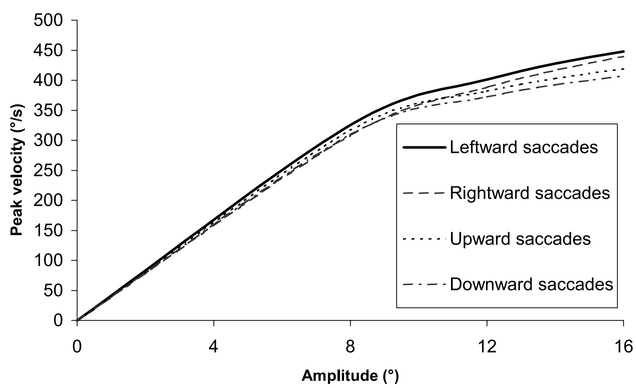


Fig. 1. The main sequence: the relationship between saccade peak velocities and their amplitudes

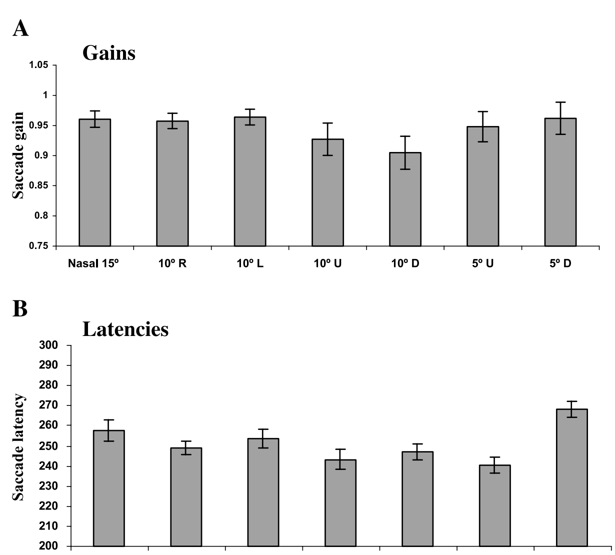


Fig. 2. Mean saccadic (A) gains and (B) latencies (ms), (SE) for rightward (R), leftward (L), upward (U) and downward (D) target steps.

saccades or between rightward versus leftward saccades (Table 2). However, asymptotic peak velocities were significantly lower for vertical saccades ($p < 0.0001$) compared to horizontal saccades (Fig. 1, Table 2). The lower asymptotic peak velocity values for vertical saccades may be attributed to the lower amplitude of saccades (in response to ±5° and 10° target steps), used to compute the asymptote.

There was no association between saccadic gain or asymptotic peak velocity and age. Saccadic latency, on the other hand, decreased with increasing age. This correlation was significant for the 5° and 10° upward and downward vertical target steps on Spearman correlation tests (Table 3). Linear stepwise regression analyses further showed the effect of age on saccadic latency (Fig. 3). The regression models were significant for vertical saccades ($p \leqslant 0.005$) with standardized $\beta$ coefficient between −0.45 and −0.63. Saccadic latency decreased between 25 and 60 ms across the 8–19 age range of the participants, depending on saccadic size and direction. Independent Student $t$-tests showed no significant difference in saccadic gains and latencies between males and females.

## 4. Discussion

The main findings of the investigation were that saccadic latencies decreased with increasing age, while saccadic gains and asymptotic peak velocities did not vary with age.

Saccadic gains in children aged 8–19 years were in the same range as values reported in adult studies for similar target amplitudes and directions (Collewijn et al., 1988a; Huaman & Sharpe, 1993; Sharpe & Zackon, 1987). However, a study on vertical saccades in four adults reported that vertical saccades were less accurate than horizontal saccades and that upward saccades undershot the target while downward saccades overshot the target (Collewijn, Erkelens, & Steinman, 1988b). These findings were not substantiated by statistical tests. Upward saccadic gain for 10° target amplitude was however, similar to that measured in our study. Our findings are also in agreement with studies on horizontal saccadic gains in children (Accardo et al., 1992; Lasker, Denckla, & Zee, 2003), which reported saccadic gains close to unity in children aged 6–12 years.

Horizontal and vertical asymptotic peak velocities, although similar to values reported in adults (Abel, Troost, & Dell'Osso, 1983; Collewijn et al., 1988a; Huaman & Sharpe, 1993; Schmidt, Abel, Dell'Osso, & Daroff, 1979), were lower than the asymptotic horizontal peak velocities reported in children of similar age (Accardo et al., 1992; Fioravanti et al., 1995). Asymptotic peak velocities vary with the recording technique among studies (Yee et al., 1985), or the saccadic amplitude range. The saccadic amplitudes in this investigation (8–16° for horizontal saccades) determined the best-fit exponential curve used to compute asymptotic peak velocities. The lower amplitudes, which were typical of the vertical saccades recorded in our investigation, likely led to lower asymptotic peak velocities (Sharpe & Zackon, 1987; Collewijn et al., 1988a).

Table 3
Correlation between age and saccadic latencies and gains by target amplitude and direction

| | Number of participants | Saccadic latency | | Saccadic gain | |
|---|---|---|---|---|---|
| | | $r$[a] | $p$ value[b] | $r$ | $p$ value |
| Nasal 15° | 34 | −0.368 | 0.032 | 0.141 | 0.425 |
| Rightward 10° | 39 | −0.388 | 0.015 | 0.226 | 0.166 |
| Leftward 10° | 39 | −0.280 | 0.085 | 0.368 | 0.021 |
| Upward 10° | 33 | −0.550 | 0.001 | 0.021 | 0.907 |
| Downward 10° | 34 | −0.625 | <0.0001 | 0.118 | 0.508 |
| Upward 5° | 36 | −0.437 | 0.008 | −0.006 | 0.974 |
| Downward 5° | 37 | −0.531 | 0.001 | −0.079 | 0.640 |

Saccadic latencies decreased with age while saccadic gain did not correlate age.
[a] $r$ is the Spearman correlation coefficient.
[b] Significance defined at $p < 0.01$.

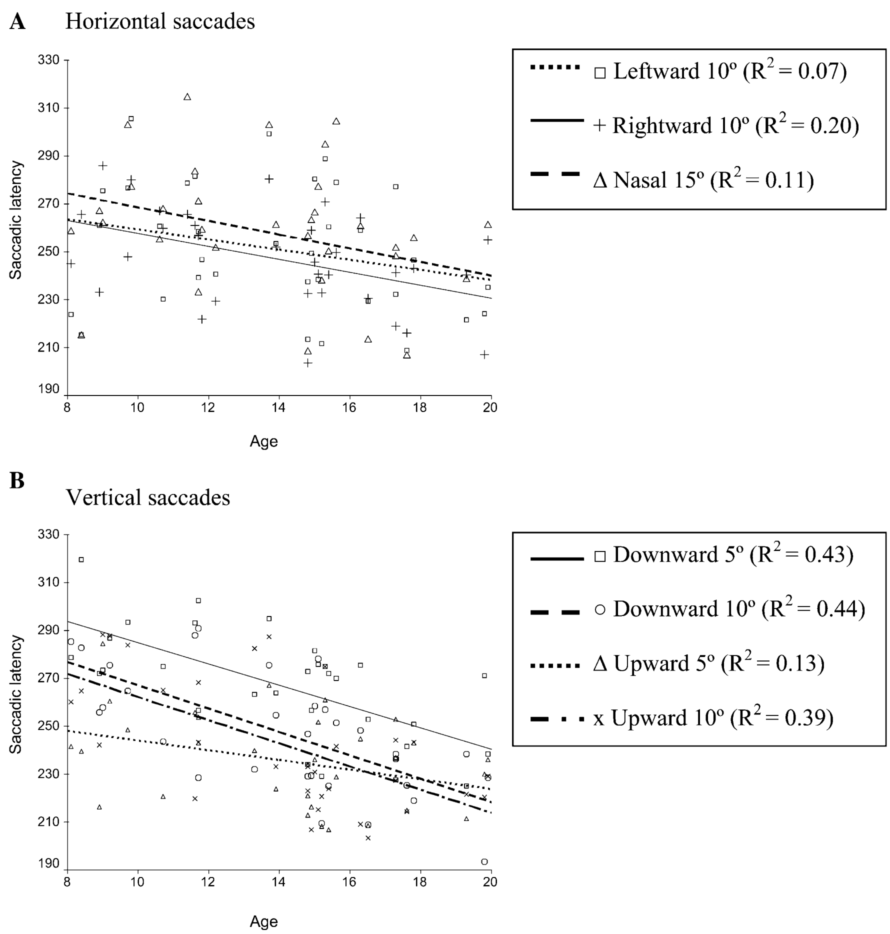


Fig. 3. Saccadic latency and age. Scatter plots of mean saccadic latency (ms) for each participant for (A) horizontal and (B) vertical target steps of varying amplitudes in relationship to age in years. Best line fit and $R^2$ (Rsq) values are shown. Latency decreased with increasing age.

Children had longer saccadic latencies compared to saccadic latencies in adults (Huaman & Sharpe, 1993; Sharpe & Zackon, 1987; Yang, Bucci, & Kapoula, 2002). Longer saccadic latency in children compared with adults has been reported in previous studies (Cohen & Ross, 1978; Kapoula & Bucci, 2002; Lasker et al., 2003 ; Leat, Shute, & Westall, 1999; Munoz, Broughton, Goldring, & Armstrong, 1998; Ross et al., 1994; Yang et al., 2002). One study (Fukushima et al., 2000) reported decreasing saccadic latency with age until age 12 years when adult values are reached. However, a study using infrared oculography reported no difference in saccadic latency in six children aged 7 to 11 years compared to adults (Accardo et al., 1992).

The reduction in saccadic latencies as age increases may reflect shorter saccadic processing time as the brain develops. Indeed, longer saccadic latency in children may reflect the immaturity of several processes, such as disengaging visual attention, a shift of visual attention to the new target, disengagement of fixation, or translation from sensory to motor coordinates (Sharpe & Zackon, 1987; Yang et al., 2002). Developmental maturation is related to brain myelination, which progresses from dorsal to ventral brain regions. Frontal and posterior parietal cortices, which are involved in visually guided saccade processing (Sharpe & Zackon, 1987), continue to acquire myelin, albeit at a slow rate after the age of 2 years, throughout childhood (Barkovich, 2000). Cerebral white matter continues to myelinate well into the third decade (Barkovich, 2000).

Values of saccadic latencies and peak velocities used to plot the main sequence curves in this study are not absolute, being limited by the sampling rate (120 Hz) of the eye tracker. A larger study with more children and saccadic trials per participant may detect small changes or non-linear trends in saccadic gain or peak velocity development. No gender differences in saccades were present. One study in children age 8 to 15 years also reported no gender difference in saccades (Ross et al., 1994).

In conclusion, our findings provide evidence for the maturity of the neural circuits in the brainstem and cerebellum that are responsible for making saccades accurate and fast in children as young as 8 years of age. This contrasts with saccade latency, which decreases as the rest of the neural network that processes saccades matures. Recording eye movements in children is difficult and challenging. The use of a non-invasive and well-tolerated eye tracker system in a relatively large number of children provides a quantitative and reliable assessment of development of the saccadic system.

## Conflict of interest

Dr. M. Eizenman is the developer of the tracker. He has shares and interest in El Mar Inc., the manufacturer of the eye tracker.


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