Infant saccades are not slow

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Saccadic eye movements are essential for redirecting the fovea at different visual targets. In adults and children saccades are remarkably stereotyped. Peak velocity and duration of saccades are a simple function of saccade amplitude called the ‘main sequence’. Saccades that are substantially slower than normal often reflect disease of the brain stem saccade generator but may also be associated with diseases of higher level structures including the cerebral hemispheres and superior colliculus. However, little is known about the speed of saccades in infancy. A single previous study reported that infant saccades may be similar to or slower than those of adults, but few saccades were recorded. The present study re-examined this issue with the technique of measuring optokinetic (OKN) quick phases, which are readily elicited from healthy and sick infants, with a view to using saccade speed as a quantitative neurological measure. We measured the duration and peak velocity of saccades (main sequence) using direct-current electo-oculography from OKN quick phases in 18 infants (nine males, nine females) aged 2 to 18 months (mean age 8mo [SD 4]) and seven adult comparison participants (four males, three females; age range 21–32y, mean age 27y [SD 3]). All infant saccades showed typical relationships between duration, peak velocity, and amplitude. Overall, there was no statistically significant difference between adult and infant main sequences for duration or peak velocity. However, the differences in the main sequence for duration almost reached significance (p=0.051) for infant saccades being faster than adults. Individual differences were also present, and some infants produced saccades faster than adults, but not slower. There was no significant age trend. We conclude that measuring saccade speed is practicable in the young infant. From the age of at least 3 months, infants generate saccades with speeds similar to or slightly higher than those of adults.

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There are three main impediments to quantifying infant saccade speeds. First, calibration is difficult because of the spatial uncertainty from the inherent disymmetry and because it is not known precisely where the infant’s visual attention is directed. Second, the time window of alertness and cooperation limits the number of saccades that can be recorded, and it is necessary to elicit a large number of saccades over a range of amplitudes to define a statistically meaningful main sequence. Third, mental fatigue and lack of alertness itself produces slow saccades in adults.\textsuperscript{13} In a previous study\textsuperscript{14} we demonstrated that the temporal characteristics of horizontal saccades and optokinetic (OKN) quick phases are similar. These reflexive quick phases require little cooperation and can be accumulated quickly over a range of amplitudes. Thus, in the present study we assessed the speed of OKN quick phases, which are simple to elicit, as a substitute for assessing the speed of saccades. One previous study has considered the temporal characteristics of OKN quick phases in infants.\textsuperscript{15} It was reported that the slope of the main sequence for peak velocity in infants was lower than that of adults, which suggests that infants have slower OKN quick phases. However, in that study, only the slope of the peak velocity main sequence was considered and the amplitudes of the quick phases elicited were small (less than 10°). In the present study we examined the main sequence for peak velocity and for duration of horizontal OKN quick phases over a large range of amplitudes, and used the slope and intercept for statistical analysis.

**Method**

**PARTICIPANTS**

This study was conducted at Great Ormond Street Hospital and the Institute of Child Health. Infant participants were the healthy children of University College London and hospital staff. Twenty infants were recruited and useful recordings were obtained from 18 (nine males, nine females); their ages ranged from 2 to 18 months (mean 8mo [SD 4]). Ethical approval was obtained from Great Ormond Street Hospital for Children NHS Trust and the Institute of Child Health Research Ethics Committee. Details of the test were explained orally and in writing to the parents, and each signed an informed consent form. All testing was conducted at Great Ormond Street Hospital.

All the infants underwent a full ophthalmic examination. This included: (1) measurement of visual acuity (Cardiff acuity cards), or in the case of the youngest infants, the ability to fix and follow a small target; (2) cover test, assessment of ocular motility and pupil reactions; (3) Lang stereo test\textsuperscript{16} in the children 6 months and older; (4) examination of the anterior segment and fundus; and (5) a non-cycloplegic refraction. No abnormality was discovered in any of the infants.

Seven adult participants (four males, three females; mean age 27y [SD 3] range 21–32y), naive to the specific hypothesis being tested, acted as a comparison group. Four of the comparison group were emmetropic and the other three wore their refractive correction during testing. None had any known neurological disorder. Although the number of comparison participants tested was small, the slope and intercept main sequence values were very similar to those previously recorded from 10 participants in our laboratory with the same equipment.\textsuperscript{14}

**RECORDING METHODS**

Horizontal eye movements were measured with bi-temporal direct-current coupled electro-oculography (EOG). Self-adhesive silver/silver chloride electrodes were placed at the outer canthus of each eye, and a common-mode reference electrode was sited at the mid-forehead. Eye movements were digitized and sampled at 1090Hz then recorded on an 8-channel digital audio tape recorder (Biologic DTR-1800; Biologic Instruments, Claix, France) with 14-bit precision and were also monitored in real time on an oscilloscope. The eye position data was filtered using a zero phase low pass digital filter (3dB point=64Hz) and differentiated to give an estimate of eye velocity.

The participants were also monitored by a video camera at all times. The EOG signal was superimposed on the video image allowing the eye movement trace and the visual appearance of the eyes to be examined together.\textsuperscript{17,18} The comments of the two operators and the vocalizations of the participant were also recorded on both the video and digital audio tapes, allowing easy cross-referencing for the offline selection of the most

<table>
<thead>
<tr>
<th>Table I: Mean slow-phase velocity gains at each stimulus speed</th>
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<tbody>
<tr>
<td><strong>Stimulus velocity (°/s)</strong></td>
</tr>
<tr>
<td>Infants</td>
</tr>
<tr>
<td>30</td>
</tr>
<tr>
<td>60</td>
</tr>
<tr>
<td>90</td>
</tr>
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<td>25</td>
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<td>50</td>
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<tr>
<td>75</td>
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**Figure 1:** Slow-phase velocity gain plotted against stimulus speed. Data were collapsed across infants to form three age groups of 2 to 6 months (six infants), 6 to 10 months (seven infants), and 10 to 18 months (five infants). Error bars show standard error of mean of means. Note that infants were closer to stimulus than adults and so had higher stimulus speeds (see Method).
Infants sat upright on a parent’s lap facing the stimulus. The parent was asked to gently restrain the head during testing in order to minimize head movement. The adult participants had their heads stabilized on a chin rest built into a vestibular chair at 75 cm from the stimulus. Saccades (for calibration) were tested first, followed by horizontal OKN.

### CALIBRATION

Two toy dogs were used as targets, each being 12 cm high and 6 cm wide, with a red light-emitting diode light at the centre of the top of the head. The toy dogs were positioned on a stand so that the light-emitting diode lights were 18.5 cm each side of the primary position. The right and left light-emitting diode lights were alternately illuminated and the toy dogs made noises to attract the infant’s attention. The operator commented on the infant’s behaviour, making special note of when saccades were appropriate to the target. The goal was to elicit as many saccades as possible until the infant became restless or inattentive, and the stand was moved to at least three different positions (between 106 and 35 cm from the infant, i.e. between 10 and 30° apart across the midline). Five to 10 saccades were elicited at each stand position.

### Table II: Main sequence parameters (mean [SD]) for optokinetic quick phases with amplitudes between 4 and 30°

<table>
<thead>
<tr>
<th>Group</th>
<th>Duration–amplitude</th>
<th>Peak velocity–amplitude</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>S, ms/°</td>
<td>I, ms</td>
</tr>
<tr>
<td>Infants</td>
<td>2.37 (0.60)</td>
<td>21.92 (4.76)</td>
</tr>
<tr>
<td>Adults</td>
<td>2.37 (0.21)</td>
<td>21.59 (1.33)</td>
</tr>
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Slope (S) and intercept (I) for main sequence for duration–amplitude relation were obtained from a linear regression of main sequence for duration. Corresponding values for peak velocity–amplitude relation were obtained from a linear regression of logged main sequence for peak velocity, such that peak velocity = 10^S amplitude.¹

### Figure 2: Horizontal optokinetic (OKN) quick-phase amplitudes. Histogram shows distribution of amplitudes of all OKN quick phases elicited in this experiment.

### DATA ANALYSIS

The video recording of the calibration procedure was studied offline. Only movements between the targets in which the infant seemed to be attentive and that were directionally appropriate were included in the calibration measurement. Eye movements associated with blinks or head movements were also discarded. For each infant, an average of 21 (SD 7) complete eye excursions were identified that could be used for the calibration measurement.

We used a standard calibration procedure. The change in EOG voltage (millivolts) corresponding to each complete eye excursion between the two targets (including secondary, tertiary, etc., saccades) was measured interactively by placing a cursor at the beginning and the end of the sequence of saccades. EOG drift was negligible over the duration of each individual saccade. For each infant, the change in EOG voltage for each saccadic sequence was plotted against the corresponding target separation (measured in degrees). In most sessions there was a linear relationship, and a regression line fitted to this plot allowed a conversion of the recorded signal from millivolts into degrees.

Our standard computer program, implemented in MATLAB, was used to determine the characteristics of the OKN data. First, the program picked out all the OKN quick phases. A quick phase was detected when the velocity was continuously above 100°/s for at least five points. This high threshold was chosen to avoid the accidental detection of slow phases. The peak velocity of each quick phase was then determined. Onset and offset of the quick phase were then defined as the last points each side of the peak velocity before which the velocity fell below 10°/s. These points were used to calculate the amplitude and duration of the quick phases.

We also examined the slow phases of OKN. To avoid any overlap with the OKN quick phases, we marked the start of the slow phases not at our defined end of the quick phases, but only after the acceleration had crossed a 0°/s² threshold. The end of the slow phase was also determined by a 0°/s² threshold, and the average velocity for each slow phase was calculated. At each stimulus speed, the mean of all slow-phase velocities (excluding those affected by blinks or head movements) was divided by the stimulus speed to give OKN slow-phase gain.

### Results

**SACCADIES**

All infants in the study frequently made multiple hypometric saccades during the calibration procedure. We elicited a total of 446 infant saccade sequences. In 24.6% of these, the infants made a single saccade to the target, in 53.1% there were two saccades in a sequence, 16.8% three, 5.4% four, and 0.1% five. There were never more than five saccades in any sequence.
In contrast, the adult comparison group tended to make a large primary saccade followed by one, or occasionally two, small corrective saccades. Very few infant sequences had a primary hypermetric saccade; only 17 (3.8%) sequences had secondary saccades that were in the opposite direction to the primary. This was similar to the adult comparison group (2.5%).

**HORIZONTAL OKN SLOW PHASE VELOCITY**

Examination of slow-phase responses showed a prompt response to curtain speed. We plotted slow-phase velocity against time for each stimulus speed, in each direction, and linear regressions of these plots showed only very small changes in slow-phase velocity within an episode. There was no slow build-up of OKN whether the curtain started from rest or accelerated to a higher speed, and no slow ‘build-down’ when the curtain speed decreased or reversed.

The average slow-phase gain at each stimulus speed was calculated for each infant and adult. For a given stimulus speed, leftward and rightward episodes were combined to yield one measure of slow-phase velocity. Infants had lower slow-phase velocity gains than adults, and there was a tendency for gain to increase with age (Fig. 1 and Table I). Gain decreased with increasing stimulus speed in both infants and adults (Fig. 1 and Table I).

**HORIZONTAL OKN QUICK PHASES**

The rate of quick phase production (beat frequency) was calculated at each stimulus speed. Infants had a lower beat frequency than adult participants (infants’ mean beat frequency over all stimulus velocities was 1.1Hz [SD 0.3]; for adults it was 3.2Hz [SD 0.3]). As infants made less frequent quick phases, their quick-phase amplitudes were higher. These amplitudes ranged up to 60°, whereas adults made very few quick phases above 30° (Fig. 2). Because adults rarely made quick phases greater than 30° we restricted our analysis of OKN quick phases to amplitudes between 4 (above which the adult main sequence was reasonably linear) and 30°.

**The main sequence for duration**

We plotted main sequences for duration (between 4 and 30°) for each infant and adult participant and fitted these plots with a linear regression. The infants’ OKN quick phases often

![Figure 3: Main sequence for duration and peak velocity. Representative scatter plots of optokinetic (a, b) quick-phase duration against amplitude and (c, d) logarithmic plots of peak velocity against amplitude for two infants aged 6 months. Left and right eye movements are plotted together and only amplitudes between 4 and 30° are shown because this range was used for analysis. Dashed lines are 95% prediction intervals for adult control participants. Dotted lines are linear regressions for infant quick phases.](image-url)
fell within the 95% prediction intervals for our adult controls (Fig. 3a). When the infants’ OKN quick phases were not within the 95% prediction intervals of the adults they were usually faster – i.e. they had a shorter duration (Fig. 3b).

To compare the main sequence parameters for duration of infants and adults statistically, we used a multivariate analysis of variance, taking the slope and intercept of each individual main sequence as the dependent variables. This analysis gave a p value of 0.051 (Hotellings $T^2$ test), which indicates that the differences between infants and adults were on the edge of significance. Therefore, for amplitudes between 4 and 30˚, infants had almost statistically shorter durations, i.e. faster saccades, than adults.

The main sequence for peak velocity
Because OKN quick phase velocity is approximately a power function of amplitude, we used a logarithmic (base 10) scale to plot peak velocity against amplitude (between 4 and 30˚) for each infant and adult participant. These logarithmic plots were fitted with a linear regression and the slope and intercept values were used for statistical analysis.

The infants’ OKN quick phases frequently fell within the 95% prediction intervals for our adult controls (Fig. 3c). When the infants’ OKN quick phases were not within the 95% prediction intervals of the adults they were usually faster – i.e. they had a higher peak velocity (Fig. 3d). However, statistical testing demonstrated that for amplitudes between 4 and 30˚ there was no significant difference between infant and adult main sequences for peak velocity ($p=0.116$, Hotellings $T^2$ test).

Discussion
Our main aim was to assess the speed of infant rapid eye movements with a view to using these as a sensitive neurological test. Previous reports have suggested that healthy infant saccades are slow, and as saccade system pathology usually slows movements, this would limit the usefulness of infant saccade testing. Our main finding was that infant saccadic movements are not slow but may in fact be slightly faster than adult movements. Before discussing the key result, we first summarize our other findings.

SACCADIES
The simultaneous video, EOG, and audio recordings allowed us to review carefully each calibration saccade to the extent that we were unusually selective, ensuring as best as we could that the chosen calibration saccades were good ones. The number of saccades elicited for calibration was insufficient to draw any conclusions about the temporal characteristics of infants’ saccades. However, we did show that hypometria is a robust phenomenon in normal infants. Even by 18 months of age occasional multiple hypometric saccades were present and, thus, accuracy was still not the same as in adults. It seems, therefore, that saccade development continues into later childhood.

As reported in previous studies,6–8 we found that saccadic hypermetria is rare in infancy. Thus, as with adults and older children, persistent hypermetria should be considered abnormal. Saccadic hypermetria is often associated with cerebellar disease.3 Cerebellar disorders can be difficult to detect in infancy; examining for saccadic hypermetria may, therefore, be a worthwhile clinical investigation.8

SLOW PHASES OF OKN
Overall, infants’ horizontal OKN slow phases had lower gain and longer durations than adult slow phases. Similar findings were reported for small-field horizontal and vertical OKN.15

No slow build-up of OKN gain was present in the infants we tested. This is strong evidence that we are measuring the early, fast build-up component of OKN (OKNe) found in older children and adults, rather than the delayed, slow increase in eye velocity (OKNd) seen in animals with poor or no foveal vision.

QUICK PHASES OF HORIZONTAL OKN
We found no evidence for slow quick phases in infancy. Indeed, in our study, although the differences were not quite statistically significant, infant OKN quick phases tended to be faster than adult quick phases. We do not believe that we overestimated the quick phase speeds as a result of a miscalculation in the calibration because this would also have led to an over-estimation of the speed of the slow phases of OKN. As discussed above, we found that infants’ horizontal OKN slow phases had a lower gain than adult slow phases.

As OKN quick phases in infants are not slower than those in adults, we can assume that horizontal saccades in infants are not slower than adults. Therefore, although multiple hypometria demonstrates that infant saccades are immature, they are not slow as has previously been suggested.10

Measuring a sufficient quantity and quality of attentive saccades to assess their speed accurately is difficult in young or uncooperative patients. This study demonstrates that when studying saccades in young participants, rather than requiring saccades to elicit quick phases. This technique gives us the opportunity to determine the full range of conditions associated with abnormal saccades in infants and children and, furthermore, the simplicity of OKN testing would permit serial recordings giving objective measurement of disease progression. A full-field OKN stimulus is the ideal because the child cannot look elsewhere, but displays normally used for visual electrophysiology are probably sufficient and OKN could be tested alongside these more common diagnostic tests.

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References

**List of abbreviations**

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<tr>
<th>EOG</th>
<th>Electro-oculography</th>
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<tr>
<td>OKN</td>
<td>Optokinetic</td>
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