Binocular coordination of saccades at far and at near in children and in adults

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The goal of the study was to test the quality of binocular coordination of saccades in children and adults, and its dependency upon the viewing distance. Fourteen normal children (4.5 – 12 years old) and 10 normal adults (22 – 44 years old) participated. Two distances were studied: far (150 cm) and close (20 cm). Horizontal saccades from both eyes were recorded simultaneously by a photoelectric device. The results show (i) poor binocular coordination of saccades in children is distance dependent: coordination is particularly poor at near and could compromise single binocular vision; and (ii) post-saccadic drift analysis indicates that stability of the eyes after the saccade as well as the quality of binocular alignment during fixation are poor in children, regardless of the viewing distance. The results provide a reference for the normal development of binocular motor control and have important implications for reading in young children.

Keywords: saccade, disconjugacy, post-saccadic drift, viewing distance, development

Introduction

Binocular coordination of saccades is essential for clear vision. It allows the object of interest to fall on the fovea of each eye, which is a prerequisite for fused single binocular vision. Kapoula, Robinson, and Hain (1986) reported for the first time that the ending of horizontal saccades is asymmetric for the two eyes: the adducting (nasally directed) eye drifts nasally in the direction of the antecedent saccade, while the abducting eye has a backward small zero-latency saccade, the so-called dynamic overshoot, that causes the eyes to converge at the end of the saccade. If the eyes converge at the end of saccades, they must diverge during the saccades. Collewijn, Erkelens, and Steinman (1988) confirmed this prediction with high-quality binocular recordings. They reported substantial divergence of the eyes at the beginning of the saccade; and, at the offset of the saccade, there is still a residual divergent disconjugacy. The authors argued that the binocular disparity created by the disconjugacy can not compromise binocular vision given its small amplitude (< 1°). However, subsequently, Collewijn, Erkelens, and Steinman (1997) reported that in adults, saccade disconjugacy is more severe at close viewing distance; they attributed this to geometrical considerations (a small lateral displacement of the eyes corresponds to a large angle at close distance). It is important to recall that this aspect (i.e., the dependency of saccade disconjugacy upon viewing distance) is of particular significance for many situations of visual ergonomy (e.g., screen working and reading, because such activities take place at close distance).

Binocular coordination of saccades is particularly important for children, especially when they begin to read. Indeed, Fioravanti, Inchingolo, Pensiero, and Spanio (1995) reported that binocular coordination of saccades is poor in young children. Although in adults saccadic disconjugacy is stereotyped, most of the time it is divergent. In young children, disconjugacy is of variable sign (i.e., sometimes convergent and other times divergent). Furthermore, the amplitude of the disconjugacy is substantially larger than that of adults. These authors also described increased disconjugate post-saccadic drift in children. The binocular coordination during and after the saccades achieves adult levels only at about 10-12 years old.

The distance at which subjects made saccades in the study of Fioravanti et al. was 100 cm. To our knowledge, the quality of binocular coordination of saccades in near vision for children has not been examined; recall that reading distance is about 30-40 cm. Studies dealing with learning difficulties in reading and dyslexia suggest that poor coordination of the eyes during and after the saccades could be involved in the etiology of reading problems (Stein, Riddell, & Fowler, 1989). The first objective of this study was to provide reference data in young children on the quality of binocular coordination of saccades at close distance in a simple oculomotor task. Does proximity influence the binocular coordination the same way in adults and in children? To respond to these questions, this work compares binocular coordination of saccades in children and in adults at two distances (20 and 150 cm).
Materials and Methods

Subjects

Fourteen children and 10 adults participated in this experiment. The children’s ages ranged from 4.5–12 years: 6 children 4.5–6 years old; 4 children 7–8 years old; and, 4 children 10–12 years old. The adult’s ages ranged from 22–44 years (28.1 ± 6.2 years). All children had normal vision, and none wore spectacles. Adult subjects were all emmetropic (no refractive errors). No subjects showed visual, neurological, or psychiatric disorders or received medication. All subjects had normal motility and normal ocular alignment. Binocular vision was assessed with the Netherlands Organization of Applied Scientific Research test of stereoauctivity (TNO); all individual scores were normal, 60° of arc or better. The investigation adhered to the tenets of the Declaration of Helsinki and was approved by the institutional human experimentation committee. Informed consent was obtained from adults and children’s parents.

The experimental task was explained to the subjects and to children’s parents before the experiments. Subjects were requested to move their eyes to the light-emitting diodes (LEDs) as soon as possible and as accurately as possible after the target appearance but not before. The subject’s head was stabilized with a chin rest.

Eye Movement Recording

LEDs data collection was directed by REX software that was developed for real-time experiments and runs on a PC. Horizontal movements from both eyes were recorded simultaneously with a photoelectric device (oculometer; Bach, Bouis, & Fischer, 1983). The eye is homogeneously illuminated by infrared light. The infrared picture of the eye is projected on a special detector. From the outputs of this detector, eye position is electronically computed both in the horizontal and in the vertical directions. This system has a resolution of 1 to 5 min of arc and linear range of ±20 deg. There is no obstruction of the visual field with this recording system (Bach et al., 1983). The accuracy of this system is between 5 and 10 min of arc when the subject’s head is restricted well. Eye-position signals were digitized with a 12-bit analogue-to-digital converter, and each channel was sampled at 500 Hz.

Visual Display

The visual display consisted of LEDs placed at two isovergence circles: one at 20 cm from the subject, and the other at 150 cm. On the close circle, three LEDs were used; one was at the center and others were at ±20°. On the far circle, five LEDs were placed: one at the center, two at ±10°, and two at ±20° (see Figure 1A for the diagram of visual display).

Oculomotor Procedure

In a dark room, the subject was seated in an adapted chair with a head and chin support. The subject viewed binocularly and faced the visual display of the LEDs. The distance between the subject and the close isovergence surface was at 20 cm. The visual display of the LEDs was placed at eye level to avoid vertical eye movements.

Calibration Task

The subject viewed with both eyes and made a sequence of saccades to an LED target jumping from zero to left or right ±10° and ±20°. From these recordings were extracted the calibration factors (see “Data Analysis”). It should be noted that binocular vision was normal for all subjects as measured by the stereoauctivity TNO test (scores 60° of arc or better). Our subjects were thus fixating targets with both eyes. In addition, during each of these trials, the target remained at each location for 2 s; this was sufficiently long to allow accurate and stable fixation. A previous study confirmed the validity of such a procedure because it showed similar results obtained with calibrations taken under monocular or binocular viewing.

Main Saccade Task

Each trial started by lighting a fixation LED at the center of one of the circles (far or close). After a 2.5-s fixation period, the central LED was turned off and a lateral target LED appeared for 2 s. All target LEDs for saccades were at 20°. Saccades at far and at close, leftward and rightward, were interleaved randomly; in each block, four types of saccades were recruited two times. Adults performed 4 blocks, whereas children performed 3 or 4 blocks. Calibrations were repeated at the beginning of each block. For the youngest children, rest periods between blocks were longer; the child was seated on his or her parent’s knee with the chin of the child resting on the chin rest of the recording apparatus. Keeping a brief (2 min) recording period for a block allowed us to efficiently maintain head stabilization.

Data Analysis

Calibration factors for each eye were extracted from the saccades recorded in the calibration task; a linear function was used to fit the calibration data. From the two individual eye position traces we derived the conjugate (LE+RE)/2, and the disconjugate (LE-RE) signal. The onset and offset of conjugate saccades were determined as follows. The onset of the saccade was defined as the time when eye velocity exceeded 5% of saccadic peak velocity; the offset was when eye velocity dropped below 10°/s. These criteria are standard and...
Figure 1. A. Illustration of the possible target locations at near and at far. Examples of rightward saccades from an adult (B) and from a child (C). In the upper traces are shown the individual eye position, the left eye (dark traces), and the right eye (gray traces); the lower traces show the conjugate signal \((L+R)/2\) and the disconjugate signal \((L-R)\) plotted at different scales. Positive inflexion of the signals indicates right direction, or convergent disconjugacy. Markers \(i\), \(p\), and \(f\) indicate the beginning of saccades, the end of pulse or fast component of the saccade, and the final position before the onset of the corrective saccade. These markers are projected on the disconjugacy signal: \(i_d\), \(p_d\), and \(f_d\). The following measures were made: conjugate saccade amplitude \((p-i)\); conjugate post-saccadic drift \((f-p)\); disconjugacy of saccades \((p_d-i_d)\); and disconjugate post-saccadic drift \((f_d-p_d)\).
similar to those used by other authors (Takagi et al. 1995; Yang et al. 2002). The markers of the saccade were projected on the disconjugacy trace to determine the disconjugacy during and after the saccade (see Figure 1B and 1C). The placement of the markers by the computer was verified by one of the investigators. Eye movements in the wrong direction and movements contaminated by blinks were rejected. Although latency of eye movements is not presented here, eye movements with latencies shorter than 80 ms or longer than 1,000 ms were also excluded from the analysis. Using such criteria, 6% of the trials were rejected for all subjects except the youngest children (4.5–6 years old), for whom the rejection rate was higher (20%).

For each saccade, we examined the binocular coordination by measuring the amplitude of the disconjugacy, that is, the left eye – the right eye difference. The amplitude of the post-saccadic eye drift was measured over the period following the offset of the primary saccade until the onset of the corrective saccade. Post-saccadic eye drift could continue after the corrective saccade or change its direction. In this respect, our study of the drift is not exhaustive, but it is meant to describe the quality of binocular fixation stability in the first period after the primary saccade, which is important to process visual information immediately after the saccade (see Figure 1B and 1C). Because of the difference in variability of these parameters between children and adults, the nonparametric Kruskal-Wallis test was used to compare the parameter difference between adults and children and to test the age effects of these parameters. ANOVA was used to analyze the parameter difference between the two viewing distances.

Results

Qualitative Observations

Figure 1B shows representative binocular recordings of saccades at far and at close from an adult, and Figure 1C shows recordings from a child of 5 years. The quality of the coordination is better shown by the disconjugacy trace displayed at a high-resolution scale. It is clear from this figure that for the child, saccades are poorly coordinated, particularly at close distance. Most important, following the saccade, there is substantial post-saccadic drift, which is disconjugate for the two eyes. Even during and after the small corrective saccade that follows, the children’s eyes are poorly coordinated. Next we present quantitative data from all subjects for the disconjugacy of the primary saccade, and of the subsequent post-saccadic fixation period (i.e., the period until the onset of the corrected saccades; see “Materials and Methods”).

Binocular Coordination

Figure 2 presents the group mean values of the amplitude of the saccades (a), the disconjugacy of saccades (b), the conjugate post-saccadic drift (c), and the disconjugate post-saccadic drift (d); values are presented for far and close distances for adults and children. There is no significant difference in the mean amplitude of saccades between the leftward and rightward and between the two distances in adults or in children. Thus, saccade accuracy is good for both populations,

![Figure 2. Mean values of saccade amplitude (a), of saccade disconjugacy (b), of conjugate post-saccadic drift (c), and of disconjugate post-saccadic drift (d) for leftward or rightward saccades at far or near viewing distance in adults and in children. Vertical bars indicate the SD. The dotted line in a indicates the target position.](https://jov.arvojournals.org/)
regardless of the viewing distance. The results in Figure 2b show substantial saccade disconjugacy. For adults, the disconjugacy of the saccades increases moderately for close distance, but the difference between far and close distance is not significant (F1,9 =0.28, p = .61 for leftward, and F1,9=0.31, p = .58 for rightward). In contrast, for children, the increase of disconjugacy at close distance is accentuated (statistically significant at F1,13 =5.84, p < .05 for leftward, and F1,13 =11.66, p < .001 for rightward). There is significant difference of saccade disconjugacy for saccades at close between adults and children (H = 4.89, p < .05 for leftward saccades; H = 6.01, p < .05 for rightward saccades), whereas for the saccades at far, the difference is not significant (H = 0.24, p = .61, and H = 0.11, p = .74, for leftward and rightward saccades, respectively). For children at close distance, the average disconjugacy of the saccades is more than 2°, that is about 10% of the size of the saccade; such disconjugacy could cause disparity and double vision (see “Discussion”).

**Conjugate Post-Saccadic Drift**

Conjugate post-saccadic drift for children shows larger drift amplitude than for adults. The nonparametric tests show significant differences between children and adults for saccades at far (H = 4.71, p < .05, and H = 3.92, p < .05, for leftward and rightward saccades, respectively), and at close (H = 17.41, p < .01, and H = 4.12, p < .05, for leftward and rightward saccades, respectively). There is no significant difference of the conjugate post-saccadic drift between far and close both in adults and in children (all p > .05). The conjugate drift in adults corresponds to about 2% of the saccade amplitude, whereas for children it corresponds to about 5%. Thus, the stability of the eyes just after the saccades is poor in children relative to adults, and this is the case for any viewing distance.

**Disconjugate Post-Saccadic Drift**

In adults, disconjugacy of post-saccadic drift is large for saccades at close, and significantly different from the far distance (F1,9=5.92, p < .05, for leftward, and F1,9=4.95, p < .05, for rightward). In contrast, in children, the disconjugacy of post-saccadic drift is large for both distances and does not significantly differ between far and close conditions (p > .05 for both directions). Comparing children and adults, the difference in disconjugate post-saccadic drift is significance for the far distance (H =13.31, p < .01, and H = 8.36, p < .01, for leftward and rightward saccades, respectively), but not for the close distance (H =2.25, p = .15, for leftward, and H =2.07, p = .21, for rightward).

In summary, distance has no effect on the accuracy of the saccades in adults or in children. In contrast, it does influence the disconjugacy of the saccades being larger at close distance. This phenomenon is more pronounced in children. Finally, the amplitude of drift and its disconjugacy tend to be larger in children for both distances.

**Developmental Aspects**

Here we examine how different parameters change within the children’s group. The children were divided into three groups (6 children 4.5–6 years old; 4 children 7–8 years old; 4 children 10–12 years old). Figure 3 shows the data for conjugate saccade amplitude (a), for conjugate post-saccadic drift (b), for the disconjugacy of saccade amplitude (c), and for the disconjugacy of post-saccadic drift (d). There is no significant change in saccade amplitude (e.g., saccades are accurate for all children’s groups and similar to those for adults). Drift at far distance is stable for children of all ages although higher than that of adults (p < .05). At close distance,
there is a progressive decrease with age. The clearest developmental changes are shown in Figure 3c and 3d, which describe the quality of binocular coordination of the eyes during and after the saccade. The disconjugacy for saccades in either distance decreases significantly with the children’s age and reaches adult values at the age of 10–12 years. Complementary results about the sign of children’s saccade disconjugacy are shown in Table 1. For adults, the disconjugacy is predominantly divergent, 80% and 84% for saccades at close and at far, whereas for children this percentage is smaller and increases gradually. These observations are in agreement with the study of Fioravanti, Inchingolo, Pensiero, and Spanio (1995). For post-saccadic drifts, the rates of occurrence of divergent disconjugacy are similar for children and for adults, and there is no consistent trend over children’s age.

<table>
<thead>
<tr>
<th>Saccade Disconjugacy (%)</th>
<th>Post-Saccadic Drift (%)</th>
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<tbody>
<tr>
<td>Far</td>
<td>Close</td>
</tr>
<tr>
<td>4.5-6y</td>
<td>70</td>
</tr>
<tr>
<td>7-8y</td>
<td>66</td>
</tr>
<tr>
<td>10-12y</td>
<td>73</td>
</tr>
<tr>
<td>Adults</td>
<td>84</td>
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In summary, the data examined across children’s ages show substantial development of the two parameters describing the binocular coordination, that is, the saccadic disconjugacy and the disconjugacy of post-saccadic drift. The most dramatic improvement occurs at 7–8 years old, approaching adult values at 10–12 years old.

## Discussion

### Poor Binocular Coordination at Close in Children

This study demonstrated that the binocular coordination of the eyes during the saccade and after the saccade is poor in children, especially for the youngest children (4.5–6 years old). The results are in agreement with prior studies (Collewijn et al., 1988; Fioravanti et al., 1995). The new finding here is that the saccade disconjugacy in children is dramatically deteriorated at close distance, more than it was known for adults (Collewijn et al., 1988).

### Physiological Mechanisms – Central Versus Muscular

The disconjugacy of saccades for children, particularly at close distance, could be considered a violation of Hering’s law, according to which the yoking pair of muscles of the two eyes receives equal innervation so that both eyes move together like a single organ. During the past decade, there has been extensive evidence showing some disconjugacy of saccades even for adults (Collewijn et al., 1988; Kapoula, Eggert, & Garraud, 1997). For some authors, such disconjugacy provides evidence against the existence of this law; such a view is supported by physiological studies that indicate that premotor neurons in the paramedian pontine reticular formation (PPRF) may encode saccade signals monocularly (Zhou & King 1998). Nevertheless, another view is that Hering’s law is basically true but imperfect, and can only grossly assure the coordination of the two eyes. Learning and adaptation are needed for the fine tuning of motor commands for each eye to enable normal quality of binocular coordination in adults. Learning is believed to be activated by the detection of errors by the visual system; binocular disparity at the end of saccades is probably the major error (Kapoula, Eggert, & Bucci, 1995; Kapoula, Bucci, Lavugne-Tomps, & Zamfirescu, 1998). On the other hand, disruption of binocular vision disables such learning-adaptive mechanisms. Indeed, both children and adults with strabismus and without binocular vision have decreased binocular coordination relative to normal subjects (Kapoula et al., 1997; Bucci, Kapoula, Yang, Roussat, & Brémond-Gignac, 2002). Consistently decreased adaptive capabilities to disparity images were reported in subjects with large strabismus (Bucci, Kapoula, Eggert, & Garraud, 1997). Why is binocular coordination poorer at close distance? As mentioned, Collewijn et al. (1997) attributed the increase of saccade disconjugacy at close distance to geometrical reasons. Our study indicates that the influence of distance on saccade disconjugacy is more pronounced for children than for adults and is not compatible with the geometrical consideration hypothesis. Most likely, at close distance there is a central interaction between saccades and the control of vergence. Children have to learn to tailor the saccade commands with the eyes converged at close distance to maintain the convergence angle during and after the saccades.

An alternative interpretation of the disconjugacy in younger children and its decrease with age should be discussed. Indeed, one could argue that disconjugacy results from naturally existing asymmetries of the oculomotor plants (e.g., differences in the transition function of the internal and external recti). Any muscular differences could be particularly reflected in the dynamics of the saccades, such as the peak velocity. We examined the difference for peak velocity of saccades between the two eyes in children and in adults. The data show that the disconjugacy of peak velocity is $53 \pm 22^\circ$/s and $55 \pm 25^\circ$/s at far and at close distance in children. Our observations are in line with those of Fioravanti et al. (1995). These values for adults are $44 \pm 17^\circ$/s and $52 \pm 22^\circ$/s at the two viewing distances. Although the values for young children tend to be higher than those for adults, the difference is not statistically significant for either viewing distance.
test: t22 = 1.72, p = .10, and t22 =0.26, p = .79, for far and close distance, respectively). Most important, there is not significant difference between far and close for adults (t9=1.71, p = .12) or for children (t13 =0.71, p = .49). These data clearly contradict those on the disconjugacy of the amplitude of the saccades and indicate that the disconjugacy of amplitude and of the peak velocity of saccades do not result from the same factor. Particularly, the relative invariance of disconjugacy of peak velocity with viewing distance contrasted with the increase in disconjugacy of the amplitude indicates that saccade amplitude disconjugacy cannot be accounted by muscular differences alone. Finally, the muscular asymmetric hypothesis considered above is incompatible with physiological knowledge (e.g., studies of saccades pointing out that the premotor and motor circuitry are already mature by 4 years old (Cohen & Henn, 1972; Fukushima, Hatta, & Fukushima, 2000). Asymmetric peak velocities of left and right eyes (adducted > abducted saccades) have been reported in some early studies using electro-oculography (Boghen, Troost, Daroff, Dell'Osso, & Birkett, 1974; Bird & Leech, 1976), but other studies using the infrared reflection technique provided opposite results (Fricker & Sanders, 1975; Hallett & Adams, 1980). Thus, there is no clear evidence for systematic asymmetry of peak velocity of abduction and adduction relative to the muscular properties. One should notice here that the work on other types of eye movements (e.g., horizontal pursuit) shows nasal-temporal asymmetry in young infants, particularly for the infants with congenital strabismus esotropia (Tyschen & Lisberger, 1986). However, even in that case, the asymmetry is believed to be due to cortical immaturity of visual motion-processing systems, the temporal motion relying on later cortical development of corresponding visual areas. In conclusion, the distance-dependant disconjugacy of the amplitude of saccades is most likely due to immature cortical or subcortical control of saccade signals when the eyes are converged than to muscular difference between the two eyes.

This work shows that the binocular coordination of saccades is not built-in but is a process developing through visual experience and learning. Most important, learning to improve saccade coordination also includes adjustment relative to distance (i.e., control of both vergence and saccade signals). A teleological argument would be that disconjugacy of the saccades in young children, particularly at close distance, is deliberate: it would help to stimulate and implement the adaptive learning mechanisms, which are needed throughout life to maintain good binocular coordination. Learning mechanisms are needed even in the absence of severe disorders to adapt to new spectacles, or to maintain good performance. Thus, the disconjugacy showed by the youngest children provides an image of the range of adaptive abilities that needed to be developed.

Implications for Reading

Increased disconjugacy at near distance might be interfering with vision, and word reading. Stein, Richardson, and Fowler (2000) reported that children with reading difficulties (dyslexics) tend to have inferior binocular coordination and poorer vergence control than normal readers. They also pointed that dyslexics could improve their reading ability by improving their binocular stability with orthoptic exercising. Our findings support such vision because even for the normal younger children, the disconjugacy of the saccades at near is substantial (about 2°, see Figure 2b) and could interfere with reading. Namely, it could slow down word recognition until the eyes are appropriately aligned in the word.

Importantly, drift of the eyes and disconjugacy of the drift are also significant in children and for either viewing distance (see Figure 2c). These observations are in agreement with the study of Fioravanti et al. (1995). The drift amplitudes (conjugate and disconjugate) found in children over the period of approximately 160 ms following the end of the saccade and before the onset of corrective saccade (see “Materials and Methods”) was ≥ 0.50. Drift velocity could thus be ≥ 3°/s. It is known that visual acuity degrades when image velocity exceeds 2o/s (Westheimer & McKee, 1975). Thus, poor stability and alignment of the eyes during fixation are other factors that could interfere with clear vision. Once again, the slowness of beginner readers could be partially due to such physiological imperfections of the binocular coordination of eyes during and after every saccade. Further studies of the binocular coordination of the saccades during reading tasks are needed, however, to consolidate this point.

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