Binocular Coordination of Saccades in Children with Strabismus before and after Surgery

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Purpose. To examine the quality of binocular coordination of saccades in children with various types of strabismus and the effect of strabismus surgery.

Methods. Eight subjects were tested (5–15 years old): five with convergent strabismus, three with divergent strabismus. A standard saccade paradigm was used to elicit horizontal saccades to target LEDs (5° to 15°). Saccades from both eyes were recorded simultaneously with the photograph-electric Skalar IRIS device (Delft, The Netherlands). This task was run before and about 3 weeks after strabismus surgery.

Results. Before surgery, the difference in the amplitude of the saccade between the left eye and the right eye was larger (15% of the saccade size) than in normal children of similar age. After strabismus surgery for all subjects the squint angle was reduced, and the amplitude of the disconjugacy of saccades decreased significantly, dropping to normal values (6%). As in normal children, postsaccadic eye drift (both its conjugate and its disconjugate components) was small in amplitude. The difference compared with normal subjects was that disconjugate drift did not restore the disconjugacy of the saccade itself (e.g., in normal subjects drift is convergent when saccade disconjugacy is divergent and vice versa). Rather, disconjugate drift tended to drive the eyes toward static eye misalignment (e.g., the drift was mostly convergent for convergent strabismics and divergent for divergent strabismics). Surgery had no significant effect on either component of the drift.

Conclusions. The improvement of the binocular coordination of the saccades could be due, at least partially, to central adaptive mechanisms rendered possible by surgical realignment of the eyes. Separate mechanisms control the binocular coordination of saccades and the alignment of the eyes during the postsaccadic fixation period. (*Invest Ophthalmol Vis Sci.* 2002;43:1040–1047)

Three to four percent of children develop strabismus during the first 6 years of life (see National Institutes of Health, Report of the Strabismus, Amblyopia, and Visual Processing Panel, 1999). Strabismus eye surgery is the principal method of treatment. Central adaptive mechanisms are also important for reestablishing and maintaining the alignment of the eyes after strabismus eye surgery. Indeed, Viirre et al.[1] surgically produced a small or moderate strabismus (<20°) in monkeys by recession of a single horizontal rectus muscle, and both saccades and VOR performances became inaccurate and disconjugate. A week after exposure to natural binocular visual experience, central adaptive mechanisms eliminated strabismus and restored normal saccadic and VOR gain for the two eyes. Importantly, before surgery, monkeys had normal binocular vision; loss of binocular fusion after surgical strabismus could drive adaptation to regain normal vision. In children with strabismus, particularly when strabismus occurs early in life, the development of binocular vision is deficient. We hypothesized that such deficient binocular vision disables or weakens the capacity for adaptive disconjugate oculomotor mechanisms. Another point is that the capacity for adaptation of eye alignment (static or dynamic) most likely is of limited amplitude (see Viire et al.[1]). Strabismus larger than 10° is beyond any adaptive capacity. This would explain why strabismus cannot be self-cured in the majority of cases. Our driving general hypothesis here is that loss of binocular vision, namely the loss of fusion, is important for driving the adaptive mechanisms that maintain the binocular coordination of saccades and the alignment of the eyes during the postsaccadic fixation period. Indeed, adult subjects with strabismus were found to have poor binocular coordination of the saccades, particularly those with large strabismus and complete paucity of binocular vision (e.g., Maxwell et al.,[2] Kapoula et al.,[3] and Bucci et al.[4]). Moreover, Bucci et al.[5] found that disconjugate (different for the two eyes) adaptation of saccades was not possible in subjects with large strabismus. Interestingly, in the same study, subjects with weak or moderate strabismus (≤10°) showed adaptation similar to normal subjects. This contrasts our initial hypothesis and suggests that low-level peripheral vision could be sufficient to drive adaptation of saccade amplitude.

To our knowledge studies of binocular motor control in children with strabismus are rather scarce. Inchingolo et al.[6] explored the improvement of the postsaccadic eye drift after strabismus surgery, but nothing is known about the quality of the binocular coordination of saccades in such subjects.

In fact, there are very few reference data on the quality of binocular coordination of saccades, even for children without strabismus. The single existing study is that of Fioravanti et al.[7] They recorded horizontal saccades from both eyes by using their own infrared limbus-tracking system (Accardo et al.[8]). Visually guided horizontal saccades were elicited on an isovergence LED circle, placed at 1 m from the subject. Target jumps were in a range from 0° to 25° with steps of 5°. They examined 12 normal children aged between 5 and 13 years. They showed that binocular coordination of saccades attained the adult characteristics at approximately 10 years: for young children (≤9 years) saccade disconjugacy was large and usually convergent (1.97°), whereas for older children (≥11 years) disconjugacy was small and most frequently divergent as in adults (0.63°). The authors explained these differences by the immaturity of

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Supported by INSERM (contract no. 4M105E), Fondation Singer-Polignac (MPB), and MENRT (QY).

Submitted for publication May 21, 2001; revised November 2, 2001; accepted November 30, 2001.

Commercial relationships policy: N.

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Investigative Ophthalmology & Visual Science, April 2002, Vol. 43, No. 4

Table 1. Clinical Characteristics of Children

				Before Surgery				After Surgery	
Subject*	**Age (y)**	**Corrected Visual Acuity (LE, RE)**	**Dominant Eye**	**Angle of Strabismus (prism D)**	**Stereoacuity (TNO Test)**	**Surgical Treatment†**	**Time from Surgery**	**Angle of Strabismus (prism D)**	**Stereoacuity (TNO Test)**
1	5	10/10 10/10	RE	25 ET far 40 ET close	—	MR both eyes[a,b] IO both eyes[a]	4 weeks	2-ET	—
2	7	8/10 8/10	LE	32-ET far 45-ET close	—	MR both eyes[a,b]	2 weeks	2-ET	30″
6	15	8/10 8/10	RE	46-ET	240″ with prism correction on	MR both eyes[a]	5 weeks	4-ET	120″
7	10	8/10 8/10	LE	35-ET	—	MR both eyes[a]	4 weeks	10 ET	—
8	10	10/10 10/10	RE	30-ET	—	MR both eyes[a,b]	2 weeks	4-ET	—
3	6	8/10 9/10	RE	22-X, XX	60″	LR both[a] eyes	2 weeks	ortho	60″
4	11	10/10 10/10	LE	30-X, XX	40″	LR both eyes[a]; SR of LE[a]	8 weeks	8-XX	40″
5	15	10/10 8/10	LE	30-X	—	LR of RE[a]	5 months	10-X	—

* Subjects are numbered according to order of mention in text.
† Superscripts indicate a for recession and b for Cupper technique.

adaptive mechanisms in younger children needed to compensate for ongoing changes and asymmetries of the oculomotor plants.

The goal of the present study was first to examine the natural quality of binocular coordination of saccades in children with moderate to large strabismus. The second objective was to examine possible modifications of the coordination of saccades after strabismus surgery.

Methods

Subjects

Eight children (5–15 years old) with moderate to large strabismus (≤46 Δ) participated to this study. The investigation adhered to the principles of the Declaration of Helsinki and was approved by our institutional human experimentation committee. Informed parental consent was obtained for each subject after the nature of the procedure had been explained. Clinical characteristics of each child are shown in Table 1; subjects are numbered in order of mention in the text of this article. The day before surgery all subjects underwent a complete ophthalmological-orthoptic examination. Corrected visual acuity was 8/10 or better for both eyes for all subjects. Five subjects had convergent strabismus, and, for two of them (subjects 1 and 2), strabismus depended on viewing distance. The three other subjects (subjects 3, 4, and 5) had divergent strabismus that was constant only in subject 5. Strabismus had appeared early (before the age of 2) for four subjects and later for the other four subjects (2, 3, 4, and 6). Only three subjects had binocular visual capability (examined with the TNO test of stereoacuity): subject 6 with late-onset strabismus when corrected with a prism, and subjects 3 and 4 with intermittent divergent strabismus.

All subjects underwent strabismus surgery (recession of 3–4 mm) of one or two muscles of one or both eyes; for three subjects the Cupper technique was also applied to the operated muscles (see for details Table 1). This technique is also called posterior fixation and consists of suturing part of the rectus muscle to the sclera posterior to the equator; this creates a second functional insertion and renders the muscle weaker.[9]

After surgery, at the time indicated in Table 1 (2 weeks to 5 months) another ophthalmological-orthoptic examination was done for all subjects. At this time, the squint angle was reduced considerably (≤10Δ) for all subjects. Subject 2, with late-onset or acquired strabismus, gained normal binocular vision, and subject 6 improved his stereopsis capability. The two subjects, 3 and 4, who showed stereopsis before surgery maintained the same level afterward.

Eye Movement Recording

The stimulation and the data collection were directed by REX, software developed for real-time experiments and run on a PC. Horizontal eye movements from both eyes were recorded simultaneously with a photoelectric device mounted on spectacles (IRIS; Skalar, Delft, The Netherlands). This system has an optimal resolution of 2″ of arc, a range of 30° for lateral excursion and is linear within 3% for excursions up to 25°. Eye-position signals were digitized with a 12-bit analog-to-digital converter, and each channel was sampled at 500 Hz.

Oculomotor Test

The subject sat in a dark room, viewing binocularly an egocentric arc of LEDs positioned horizontally at eye level 123 cm away. The subject was seated in an adapted chair with a head support. A standard saccade paradigm was used to elicit visually guided saccades: the subject fixated a central small spot of red light (5.6″ of arc); after 800 msec the central spot disappeared and a target appeared for 900 msec at an eccentric randomly chosen position to the left or to the right at 5°, 10°, and 15°. The target was either a normal E or a backward E (0.4 × 0.2°), made by lighting different combination of segments of a seven-segment LED array. The subject was instructed to fixate the target as accurately as possible and to discriminate whether it was a normal E; target presentation was sufficiently long to allow accurate fixation. This task was done twice: the day before strabismus surgery, and 2 weeks to 5 months after the surgery.

Analysis of Data

Calibration and analysis methods are similar to those used in prior adult studies.[5,10] Briefly, calibration data were obtained by asking the subjects to fixate monocularly a light-dot presented at various horizontal positions; this was done under both monocular viewing conditions (the other eye was covered). We used monocular viewing for calibration to assure that the subject was fixating the target as precise as possible; recall that, all our subjects had good visual acuity in both eyes and could fixate the target monocularly. This procedure of calibration under monocular viewing is standard used in normal subjects (e.g., Collewijn et al.[11]) or in subjects with strabismus but without amblyopia.[4-6] To confirm further its validity for this study, for three of the subjects (2, 5, and 6), we also calibrated the data with factors extracted from a binocular viewing condition. The results produced with the two methods of calibration were almost identical. A linear function was used to fit the calibration data. From the fixation periods between saccades, i.e., at the end of each trial, we measured the eye misalignment, i.e., the degree of squint before and after surgery: the left–right eye position difference; positive values indicate convergent strabismus, negative values divergent strabismus.

Saccade onset was determined at the point where eye velocity reached 5% of the peak velocity; saccade offset was taken as the time when eye velocity dropped below 10°/sec.

For each saccade we examined the binocular coordination by measuring the amplitude of the disconjugacy, i.e., the left eye–right eye difference; we also measured the gain (saccade amplitude/target excursion, in degrees). The amplitude of the postsaccadic eye drift was measured over the period after the offset of the primary saccade until the onset of a corrective saccade. Most of the saccades were followed by a corrective saccade with latency between 180 and 350 msec. Thus, our measure of postsaccadic drift covered on average a period of 241 msec. Postsaccadic eye drift could continue after the corrective saccade or change its direction (see examples, Fig. 2). In this respect, our study of the drift is not exhaustive, but it is meant to describe the quality of binocular fixational stability in the first period after the primary saccade, which is important to process visual information immediately after the saccade. The amplitude of the drift was measured for each eye; from these measures we estimated the conjugate or cyclopean component of the drift: [(amplitude of the drift of the left eye + amplitude of the drift of the right eye)/2], and the disconjugate component, i.e., the difference in the amplitude of the drift between the left and the right eye. The disconjugacy of the saccade and the two drift components (conjugate and disconjugate) were always expressed as a ratio of the amplitude of the saccade. This was because inspection of our data indicated, at least for some subjects, a tendency for the disconjugacy to increase for larger saccade amplitudes. Note also that the same range of target excursions was used for the before and after surgery oculomotor test, and the mean amplitude of saccades obtained was similar before and after surgery (12.6 ± 2.5° and 13.1 ± 2.7°, respectively). Two types of analysis were done: one on the absolute value of the different measures, and a second on algebraic data, taking into account the sign of the disconjugacy. The sign of the disconjugate component of the postsaccadic drift was as follows: positive differences (left–right eye) indicate convergent disconjugacy and negative values divergent disconjugacy, regardless of the direction of the saccade. To evaluate the speed of saccades we measured the ratio of peak velocity over the amplitude of the saccade for each individual eye, before and after surgery.

Statistical analysis was performed using the analysis of variance (ANOVA), with subject as a random factor and the before–after surgery condition as a fixed factor. For analysis of individual results the Student's *t*-test ($P < 0.05$) was used to compare before–after surgery measures.

Results

Measure of the Squint Angle

Figure 1 shows in degrees the average angle of squint measured during our oculomotor test at the end of the fixation period of all trials. The horizontal lines indicate in degrees the squint angle measured by clinical tests (see Methods and Table 1). The eye movement–based measures were in general agreement with the clinical measures. Before surgery, small differences between the two measures of the squint angle were seen for subjects 1 and 2 (see Table 1), who had incomitant distance-dependent esotropia; a large discrepancy was observed for subject 3, who had exophoria/tropia. After surgery for all subjects the value of the residual squint angle was very similar for the two types of measurement.

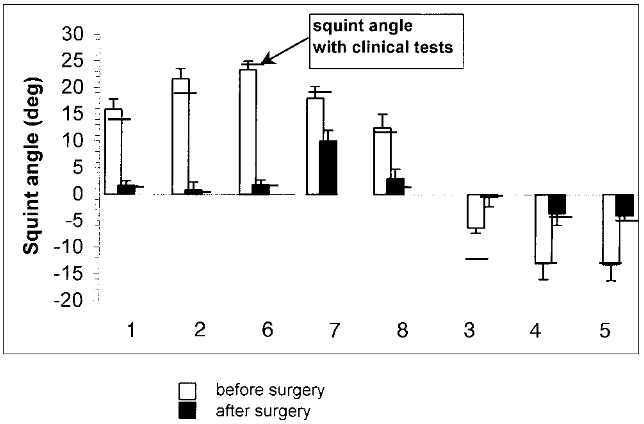

Figure 1. Individual means of the squint angle (in degrees) before and after surgery; squint is based on eye movement recordings (left eye–right eye difference measured at the time point at the end of each trial, i.e., ≥500 msec after the end of primary saccade). *Vertical lines* are the SD of each mean. *Horizontal lines* indicate, in degrees, the clinical measurement of the squint angle. Positive values indicate esodeviation or convergent strabismus; negative values indicate exodeviation. Subjects are numbered in order of mention in the text of this article.

Binocular Coordination of Saccades

Qualitative Data. Figure 2 shows sequences of saccades from subject 2 before (A) and after (B) surgery. Before surgery the right eye was esodeviated as indicated by the offset of the traces of the two eyes and also by the lower trace, indicating both the static deviation and the disconjugacy of the eyes during and after saccades. The deviation was slightly higher (about 20°, approximately 35Δ) than the value of strabismus measured clinically, and the postsaccadic drift was small. The left, dominant eye was the eye fixating the target. As shown by the disconjugacy trace, the execution of the saccades was associated with a disconjugacy or sudden change of the squint that was very variable, divergent, or convergent. Two weeks after surgery (Fig. 2B) the static deviation was considerably reduced to approximately 1° (approximately 2Δ), but convergent postsaccadic drift was still seen after some of the saccades shown. Note that the disconjugacy of the saccades was of smaller size and almost always divergent (downward inflection of the trace).

Quantitative Data. In Fig. 3A is shown the average amplitude of the disconjugacy of saccades expressed as ratio of the saccade amplitude (absolute values). Data are shown before and after surgery for each subject. Before surgery, the ratio was higher than 0.1 for all subjects. The highest values were observed for the two younger subjects (1 and 2), and for the two older subjects who had large strabismus (subject 6: 46Δ ET, and subject 5: 30Δ X). The mean ratio was 0.16 ± 0.05; this value is higher than that reported by Fioravanti et al.[7] in children without strabismus of corresponding age (approximately 0.10 for saccades of similar amplitude).

Effect of Strabismus Surgery. Recall that for all subjects, squint was considerably reduced or eliminated, as shown in Table 1 and Fig. 1. More importantly, after surgery, the disconjugacy of the saccades decreased significantly with respect to the before-surgery values ($F_{1,7} = 18.55$, $P < 0.003$). The mean ratio became 0.09 ± 0.02; this value is very similar to that of normal subjects[7] (see above). The disconjugacy decreased significantly with respect to the before values for all but two

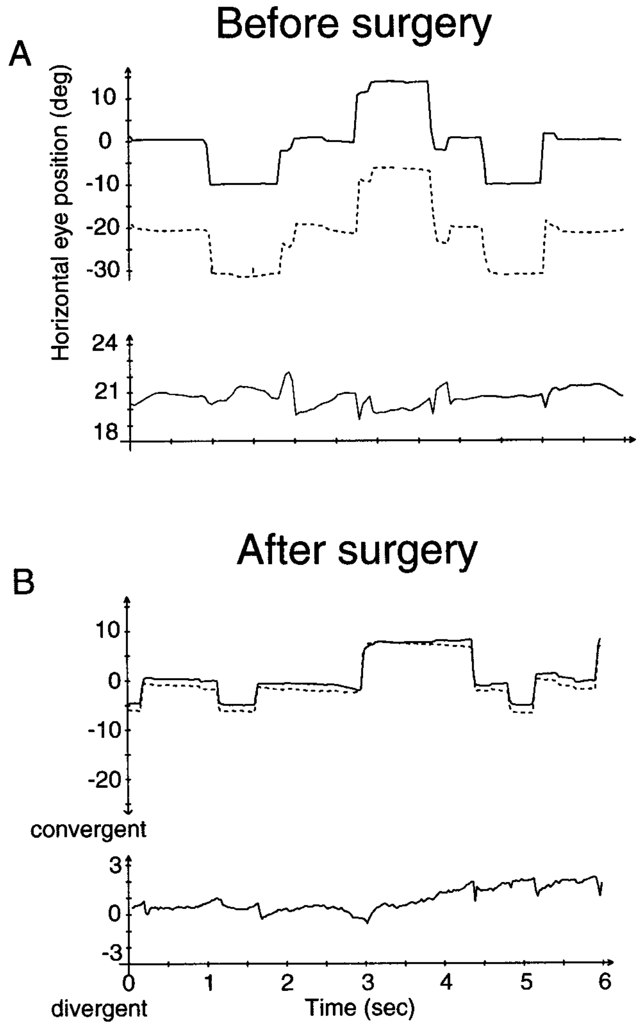

Figure 2. Binocular recordings of sequences of saccades before (**A**) and after (**B**) surgery from subject 2. Viewing was binocular. The *solid line* is the position trace of the left, dominant eye; the *dashed line* is that of the right eye; horizontal segments indicate the target position. The *lower trace* is the deviation or the disconjugacy trace (difference between the left and the right eye); upward inflection indicates convergent disconjugacy.

subjects (subjects 1 and 7; see asterisks in Fig. 3A). In contrast, there was no significant effect on the sign of the disconjugacy (not shown in the figure, $F_{1,7} = 0.20$, $P = 0.665$). Nevertheless, the variability of the sign of the disconjugacy decreased significantly after surgery: ANOVA was applied on the SD of the algebraic mean disconjugacy, with subjects as random factor and the before/after surgery condition as fixed factors. There was a significant effect ($F_{1,7} = 12.62$, $P < 0.01$), suggesting that the sign of the disconjugacy became less variable. Indeed, the percentage of saccades with divergent disconjugacy that was 47% (range, 23% to 63%) before surgery, increased to 60% (range, 46% to 87%) after surgery.

In normal adults, the disconjugacy of saccades increases under monocular viewing, relative to binocular viewing.[10] We tested this aspect in five of the subjects (1, 2, 3, 5, and 6), who performed the saccade task under binocular viewing and under both monocular viewing conditions (see Table 2). Contrary to normal subjects, in our subjects, the disconjugacy of saccades did not vary significantly with the viewing condition either before ($F_{2,8} = 0.18$, $P = 0.83$) or after surgery ($F_{2,8} = 3.22$, $P = 0.09$).

Accuracy of Saccades. The modification in saccade conjugacy brings up the question whether there was a concomitant modification in the accuracy of the saccades relative to the target location. Before surgery, the average gain (eight subjects, binocular viewing condition) was 0.88 (range, 0.72 to 0.99); after surgery, the mean gain value became 0.94 (range, 0.77 to 1.15). This mild improvement in saccade accuracy, however, did not reach statistical significance ($F_{1,7} = 0.063$, $P = 0.81$). Saccade accuracy was also evaluated by measuring the frequency of corrective saccades after the primary saccade. The average frequency of corrective saccades made by the subjects was 68%, and 64% before and after surgery, respectively; again, the mild decrease of the frequency of corrective saccades after surgery did not reach significance ($F_{1,7} = 1.694$, $P = 0.23$).

Postsaccadic Eye Drift

Figures 3B and 3C, show the conjugate and disconjugate components, respectively, of the postsaccadic eye drift expressed as a ratio of the amplitude of the saccades. Data are shown for each subject before and after surgery.

Conjugate Component. Before surgery, the drift was small in all subjects. The group mean ratio was 0.04 ± 0.03, and individual ratios ranged between 0.01 and 0.04, except for subject 7 (0.12 ± 0.09). Surgery had no significant effect on the conjugate drift ($F_{1,7} = 0.02$, $P = 0.88$; Fig. 3B). At the individual level (see asterisks in Fig. 3B), there was a significant decrease of the amplitude of the drift relative to the before values for subjects 6, 7, and 8 and a significant increase for subject 1. Note that subjects 1, 7, and 8 had all early-onset strabismus, yet drift decreased in two of them (subjects 5 and 7) and increased in subject 1, indicating no consistent pattern. Thus, overall, the conjugate drift was small in amplitude before as well as after surgery. Our observations are compatible with the study in normal children,[7] showing that conjugate drift, at least for small saccades (≤10°), is small.

Disconjugate Component. The amplitude of the disconjugate postsaccadic drift was also small for all subjects (Fig. 3C); the group mean ratio was 0.06 ± 0.02 (range of individual ratios, 0.02–0.09). For five subjects, the sign of the drift (not shown in the figure) was on average in the direction of the static offset of the eyes: drift was on average convergent for three of the five subjects with convergent strabismus (1, 2, and 8) and divergent for two of the three subjects with divergent strabismus (subjects 3 and 5). This is in agreement with the findings of Inchingolo et al.[6] in children with strabismus. Thus, in normal subjects, drift restores or reduces the disconjugacy created by the saccade, whereas in children with strabismus drift drives the eyes to the default position of the misalignment.

Strabismus surgery had no significant effect on the amplitude of the disconjugate component of the drift (absolute values, $F_{1,7} = 2.76$, $P = 0.14$); at the individual level there was no significant surgery effect for any of the subjects. There was no significant effect of surgery on the sign of the drift disconjugacy either (ANOVA was applied on the algebraic values of drift disconjugacy, $F_{1,7} = 1.64$, $P = 0.24$).

Speed of Saccades

Table 3 shows individual mean peak velocity normalized by the amplitude of saccades for the dominant and for the nondominant eye before and after surgery. Before surgery, the highest

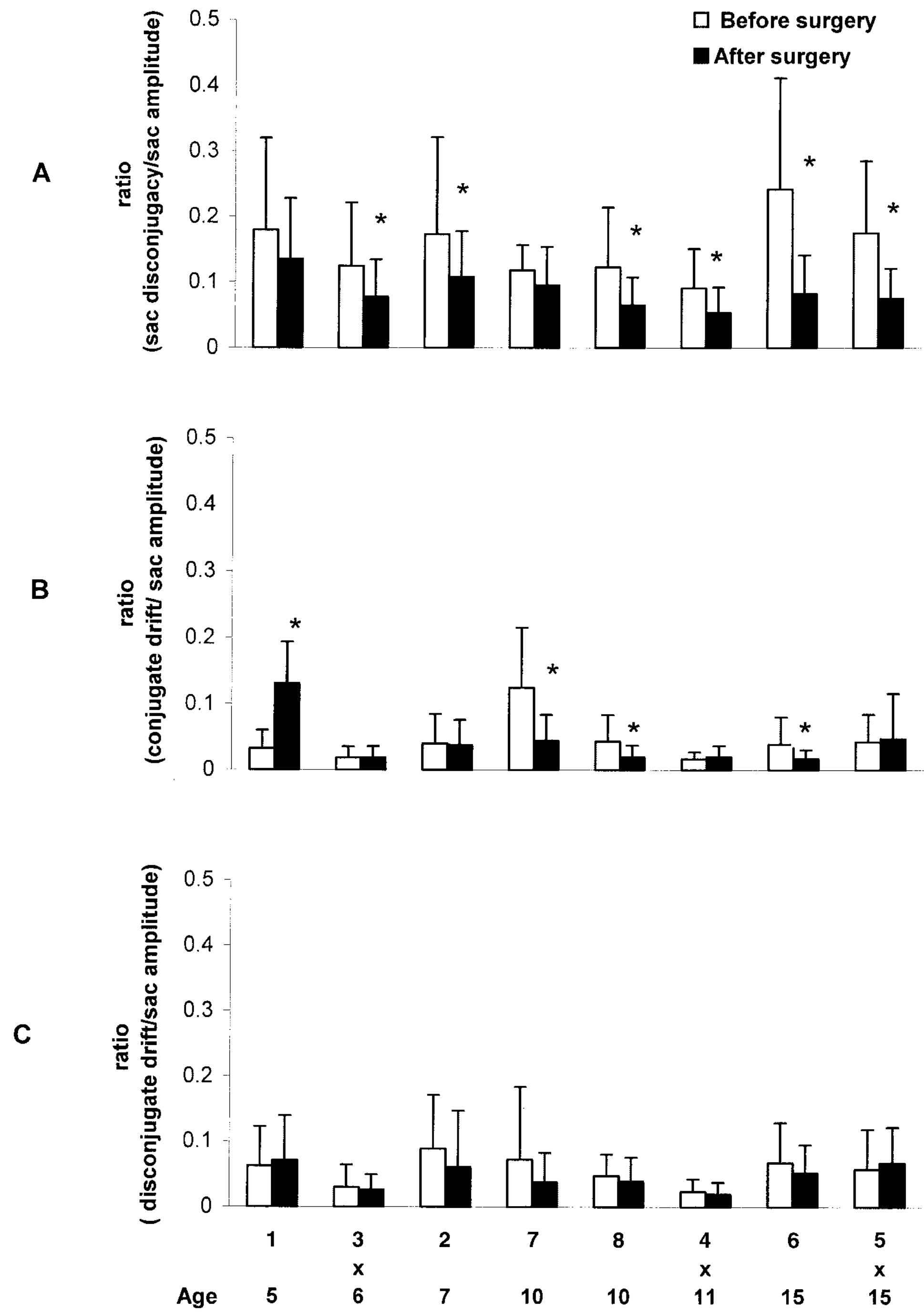

FIGURE 3. Individual average disconjugacy of saccades (**A**), of the conjugate (**B**) and disconjugate (**C**) component of postsaccadic eye drift expressed as a ratio to the amplitude of the saccade; values are shown for each subject before (*empty bars*) and after (*black bars*) surgery; the letter X indicates divergent strabismus. Rightward and leftward saccades were grouped together, because there was no consistent difference. *Vertical lines* indicate the SD. Means are based on 40 to 69 saccades before surgery and on 35 to 71 saccades after surgery. *Significant change (at $P < 0.05$) with respect to the before surgery value. Subjects are numbered in order of mention in the text of this article.

velocities were observed for the two younger subjects (1 and 3); this is compatible with observations in normal children for increased velocity of saccades in younger children relative to that of older children.[7] After surgery, saccades of the dominant eye became significantly slower for two subjects (6 and 7, Student's *t*-test comparing before–after surgery mean of normalized peak velocity, significant at $P < 0.05$); for the nondominant eye, the after surgery decrease of velocity was significant for three subjects (5, 6, and 7). There was no significant effect for the remaining five subjects. For the ensemble of the subjects, ANOVA showed no effect of the surgery in the velocity of saccades ($F_{1,7} = 1.88$, $P = 0.21$ for the dominant eye and $F_{1,7} = 3.40$, $P = 0.11$ for the nondominant eye).

Discussion

Binocular Coordination of Saccades in Strabismus

This study examined the quality of binocular coordination of horizontal saccades before and after strabismus surgery. The age of the children ranged from 5 to 15 years. Strabismus was convergent in five of the eight subjects. Before surgery, the disconjugacy of the saccades was larger than that reported for normal children of similar age.[7] Thus, binocular coordination in children with strabismus is worse than in normal subjects.

Effects of Surgery

Strabismus surgery was, at least at the time of our testing, successful because the static eye deviation was considerably

Table 2. Disconjugacy of Saccades

	Before Surgery		After Surgery	
Subject*	**DEV**	**NEDV**	**DEV**	**NDEV**
1	0.15 ± 0.13 (23)	0.17 ± 0.15 (27)	0.12 ± 0.13 (26)	0.12 ± 0.11 (34)
2	0.17 ± 0.16 (36)	0.14 ± 0.18 (41)	0.12 ± 0.15 (62)	0.12 ± 0.11 (39)
6	0.27 ± 0.30 (43)	0.25 ± 0.19 (23)	0.06 ± 0.07 (32)	0.06 ± 0.07 (33)
3	0.14 ± 0.6 (63)	0.13 ± 0.10 (40)	0.04 ± 0.04 (67)	0.04 ± 0.16 (36)
5	0.15 ± 0.17 (43)	0.16 ± 0.15 (31)	0.05 ± 0.10 (25)	0.06 ± 0.08 (31)
Mean	0.17 ± 0.18 (5)	0.16 ± 0.16 (5)	0.09 ± 0.11 (5)	0.09 ± 0.12 (5)

Values are expressed as ratio of the amplitude of the saccade before and after surgery under both monocular viewing. DEV, dominant eye viewing; NDEV, nondominant eye viewing.

* Subjects are numbered according to order of mention in text.

reduced for all subjects, and one became orthotropic. Binocular vision recovered only for two of the four children with late-onset strabismus (subjects 2 and 6). The second effect of the surgery was that the disconjugacy of the saccade was significantly reduced relative to the before-surgery values. The reduction occurred systematically regardless of the type of strabismus. In addition, the sign of the disconjugacy (convergent or divergent) became less variable than that observed before surgery.

The improvement in the conjugacy of saccades could be the direct consequence of the surgical realignment of the eyes, but most likely, it was mediated by central adaptive mechanisms, e.g., more efficient tuning of motor commands when the two eyes are aligned. In particular, the decrease of the variability of the sign of the disconjugacy argues in favor of central adaptation. Indeed, in normal adults, the existing disconjugacy of the saccades is almost systematically divergent. It has been argued that this stereotyped aspect is the result of central adaptation to properties of oculomotor plants and/or of premotor circuits innervating the lateral rectus and the medial rectus muscles (see Fioravanti et al.[7]).

If one admits the hypothesis of central adaptation, one should address the question to what extent the improvement of saccade conjugacy by surgery reflects a modification of the preferred retinal loci for positioning the eyes or a higher level binocular remapping of retinal space, leading to better motor conjugacy. Indeed, there is early evidence for a covariation of strabismus angle and retinal correspondence.[2,13,14] For subjects like subjects 2 and 6, who improved binocular vision, a binocular remapping presumably occurred and could be at the origin of the improvement of saccade conjugacy. A similar mechanism could take place even for the subjects whose strabismus was reduced but who did not develop normal measurable stereopsis (subjects 1, 5, 7, and 8). Finally, the finding that the disconjugacy of saccades did not change significantly under different viewing conditions suggests a relative constancy in the preferred retinal loci regardless of the viewing conditions. Nevertheless, our eye movement recordings do not allow to substantiate this important issue of change in preferred retinal loci before and after surgery.

Whatever the mechanism is, this study shows for the first time, dynamic harmonization of binocular coordination of saccades after strabismus surgery. The stability of this effect over time remains to be studied.

Postsaccadic Eye Drift in Strabismus

Before surgery, both the conjugate and the disconjugate component of the postsaccadic drift were small, less than the disconjugacy of the saccade itself. The surgery had no effect on the postsaccadic drift for either component.

An important aspect emerging from the ensemble of our observations is that the binocular coordination of the saccade and the binocular coordination of the drift are controlled by separate mechanisms. This is compatible with earlier monkey studies on adaptive control of saccade amplitude versus postsaccadic drift[15] and in humans[16,17]; saccade amplitude adaptive control requires readjustment of the saccade, i.e., pulse and step signals together, whereas the postsaccadic drift involves readjustment of the ratio of these components. The above-cited studies deal with conjugate mechanisms; disconjugate mechanisms controlling the postsaccadic drift could be more complex. As pointed out by Fioravanti et al.[7] the adaptive mechanism controlling the drift differently for the two eyes

Table 3. Mean Peak Velocity before and after Surgery for the Dominant and the Nondominant Eye

		Before Surgery		After Surgery	
Subject*	**Age (y)**	**Dominant Eye**	**Nondominant Eye**	**Dominant Eye**	**Nondominant Eye**
1	5	38 ± 12 (30)	39 ± 13 (30)	40 ± 18 (28)	38 ± 11 (28)
3	6	39 ± 11 (32)	38 ± 11 (32)	41 ± 11 (35)	38 ± 10 (35)
2	7	36 ± 8 (35)	39 ± 10 (35)	33 ± 7 (36)	37 ± 7 (36)
7	10	37 ± 12 (56)	36 ± 15 (56)	20 ± 6 (48)†	20 ± 8 (48)†
8	10	24 ± 8 (49)	25 ± 11 (49)	24 ± 8 (37)	25 ± 7 (37)
4	11	23 ± 5 (42)	21 ± 7 (42)	23 ± 7 (44)	21 ± 10 (44)
6	15	34 ± 9 (25)	32 ± 8 (25)	27 ± 7 (76)†	27 ± 8 (76)†
5	15	34 ± 11 (69)	33 ± 10 (69)	32 ± 7 (27)	28 ± 6 (27)†
Mean		33 ± 6 (8)	32 ± 7 (8)	30 ± 8 (8)	29 ± 7 (8)

Values in parentheses are peak velocity normalized over the amplitude of saccades.

* Subjects are numbered according to order of mention in text.

† Significantly slower compared with before surgery value; $P < 0.05$.

could be more complex and would develop later in normal children than the mechanism that control the amplitude of the saccades. In this context, our observations of the invariance of the drift in children with strabismus could be seen either as due to the immaturity of the corresponding adaptive ability or to its longer time course. Nevertheless, one should take into account that the major abnormality was in the amplitude of the saccades and this disconjugacy was decreased after surgery, thereby reducing the disparity present at the end of the saccade and thus the need for postsaccadic corrective mechanisms.

Stimulus Driving Postsaccadic Drift and Saccade Amplitude Adaptation

Our findings for the drift contradict the observations of Inchingolo et al.,[6] who found, for all subjects, significant decrease of the drift after surgery. Even though several methodological differences between the two studies exist (e.g., age of subjects, type of surgery, and evaluation of the drift over longer periods including after secondary saccades), the different results could be due to the fact that in the study of Inchingolo et al.,[6] binocular fusion was regained after surgery by all subjects. In other words, fusion could be necessary for activating the adaptive mechanism needed to reduce disconjugate postsaccadic drift. Disruption of fusion and postsaccadic retinal slip are the two signals that could drive disconjugate drift adaptation. Indeed, Kapoula et al.[17] showed that visually induced adaptation of horizontal postsaccadic drift (by drifting the images at the end of the saccade) is not possible when the images viewed by the two eyes cannot be fused. This is in contrast with a subsequent study in monkeys[18] showing that disconjugate adaptation of vertical postsaccadic drift is possible even without fusion. There might be differences, however, in the respective role of fusion and retinal slip for the horizontal and vertical adaptive system. Thus, on the basis of the data available in human studies for horizontal postsaccadic drift, we suggest that fusion might be necessary for postsaccadic drift adaptation, whereas it could be less critical for saccade amplitude adaptation. Most likely, low-level peripheral binocular or bi-ocular vision could be sufficient to drive such type of adaptation.[5] This is reminiscent of the capacity to trigger disparity vergence eye movements even when using different images for the two eyes (a circle and a cross; see Westeimer and Mitchell[19]).

Speed of Saccades

The speed of saccades for the majority of the subjects ($n = 5$) did not change after surgery. This finding is in agreement with the few reports available in the literature exploring in children the change of velocity of saccades after small recession of one eye muscle,[20,21] similar to those applied in our study. At the individual level, however, the saccades of three subjects (5, 6, and 7) became significantly slower. A similar phenomenon of slowing down of saccades has been reported by Lewis et al.[22] in adults with congenital or with acquired oculomotor paresis. Two months after surgery, static eye alignment improved as well as binocular coordination of the saccades, and saccades were found to be slower relative to the presurgery values. The authors attributed these effects to central adaptation. Our observations are also compatible with studies dealing with visually induced oculomotor adaptation of the gain of the saccades in monkeys,[23] or, more recently, in humans:[24] adapted saccades were reported to be slower. Thus, the decrease of saccade velocity reported in this study for three subjects could also be mediated by central adaptive mechanisms compensating for the changes in the oculomotor plants.

Conclusion

In conclusion, this study showed that the binocular coordination of saccades in children with strabismus was worse than has been reported in normal subjects and that strabismus surgery in addition to realign the eyes improved the binocular motor control. The improvement could be both the consequence of the realignment of the eyes, but also the result of central adaptation. In contrast, surgery had no effect on postsaccadic eye drift, indicating that separate mechanisms control the binocular coordination of the amplitude of the saccades and the binocular coordination during the postsaccadic fixation period. Perhaps the presence of sensory fusion is necessary for the disconjugate adaptation of horizontal postsaccadic drift in humans, whereas low-level peripheral binocular or bi-ocular vision is sufficient to trigger disconjugate adaptation of saccade amplitude.

Acknowledgments

The authors thank the orthoptist Marie Deschamps and Afida Afkami for conducting orthoptic examinations; France Maloumian for preparing the illustrations; and Mark Wexler for correcting the linguistic content of the manuscript.

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