

Saccades in strabismus: a literature review

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Abstract

Aim: To review evidence from the literature on the effect of concomitant strabismus on saccadic eye movements and saccade adaptation. To consider how analysis of such eye movements may provide information about the link between the coordination of saccades and binocular vision.

Method: A literature-based review of saccades in strabismus is presented.

Results: Saccade characteristics are in general unaffected by the presence of concomitant strabismus in the absence of amblyopia. The literature also documents no significant change to saccade performance following surgical intervention to the extraocular muscles despite evidence of altered velocity profiles. The main effect on saccades in strabismus is disconjugacy, which is significantly increased. There is evidence that disconjugate saccade adaptation, however, is intact in strabismus, suggesting that fusion may not be necessary for activating the adaptive mechanism.

Conclusion: Measurement of eye movement characteristics may help to give an understanding of mechanisms involved in sensory and motor adaptations to strabismus.

Key words: Esotropia, Exotropia, Saccade adaptation, Saccades, Strabismus

Introduction

Saccades are constantly being executed in any visual environment. Rapid processing of visual information, accuracy, velocity and binocular coordination of saccades are all essential for best visual performance and achieving binocular vision after every change of fixation. Studies of saccades in the presence of concomitant strabismus are not abundant but are of interest in that analysis of saccade characteristics provides information about cortical function and information about the link between binocular vision and binocular coordination of saccades.

To give an overview of the topic this review presents literature since 1966 identified from Medline using the following search terms: strabismus, eye movements,

saccades and saccade adaptation. The paper firstly considers characteristics of horizontal saccades in strabismus, in particular saccade latency, accuracy and peak velocity, and secondly literature is reviewed on the conjugacy of saccades in strabismus. Finally horizontal saccade adaptation in strabismus with and without anomalous binocular vision is considered in experimental paradigms and adaptation of saccades in real situations following surgical alignment.

Characteristics of saccades in strabismus

This section reviews the literature on the characteristics of single-target visually guided horizontal saccades in the presence of strabismus. Whilst the characteristics of saccades in normal human subjects are well documented, there are few studies that consider the characteristics in subjects with concomitant strabismus.

Saccade latency

From the appearance of a peripheral target to the onset of the eye movement, a period of time elapses to enable visual processing of the target, planning and execution of a saccade. This is known either as the initiation time, reaction time or saccadic latency. Saccades typically have latencies in the order of 200 ms.^{1,2}

Ciuffreda *et al.*^{3,4} recorded saccades using an infrared eye movement technique in strabismic and amblyopic subjects. Saccades were recorded with both eyes open, monocularly fixing with the normal eye and monocularly fixing with the strabismic or amblyopic eye. Six of 11 subjects with amblyopia, with or without strabismus, had increased saccade latency in the affected eye compared with the normal eye. For the amblyopes without strabismus ($n=3$) latency in the amblyopic eye was significantly greater than in the non-amblyopic eye. Two subjects with intermittent strabismus without associated amblyopia had no significant increases in saccade latency in the strabismic eye or differences between the fixing and strabismic eyes. These results suggest, therefore, that it is amblyopia and not strabismus that affects saccade latency.

This is supported by a more recent study by Kapoula and Bucci⁵ who report results of saccade latency in 5 children with strabismus and 5 children with normal binocular single vision (BSV). All participants had normal visual acuity. Saccade latency in the strabismic group was not significantly different from that of the binocular group. They also observed that saccade latency, in these 5 strabismic children, did not change significantly before and after strabismus surgery.

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Ciuffreda *et al.*^{3,4} suggest that increased saccade latency in amblyopes results from a processing delay in the sensory pathways from the central region of the amblyopic eye to centres involved in saccade initiation.

Griffiths⁶ studied 8 adults with constant strabismus (5 esotropic and 3 exotropic) and visual acuity in the strabismic eye of 6/24 (Sn) or better. Saccades were performed with both eyes open. Saccade latency was not significantly different from that of an age-matched control group for the two amplitudes and directions tested, indicating that information from the strabismic eye during suppression does not affect saccade latency in the fixing eye.

Changes in fixation rarely involve pure saccades. Typically in a natural environment combined movements involving saccades and vergence are required. Latencies of saccade and vergence components of combined movements are longer than those of corresponding pure movements. As individuals with strabismus lack disparity information the efficiency of such combined movements may be reduced. Bucci *et al.*⁷ investigated the latency of horizontal eye movements in 10 children with early-onset esotropia ($n=7$) and exotropia ($n=3$). They also examined the effect of surgery on these movements. The majority of strabismic children investigated showed normal latencies for combined horizontal eye movements. A few participants, particularly those with intermittent exotropia, showed longer latencies (vergence component > saccadic component). The normal results found indicate that monocular cues, presumably used by the esotropic subjects without clinically demonstrable BSV, can be as effective as normal binocular cues and in fact intermittent binocularity or reduced binocular capabilities can be associated with longer latencies in natural viewing conditions.

Saccade accuracy

The accuracy of saccades in the dominant eye of strabismic subjects has been found to be comparable to that in binocular subjects.^{6,8} van Leeuwen *et al.*⁸ studied the saccades of 10 adult subjects with constant strabismus (2 esotropic and 8 exotropic) for target amplitudes ranging from 5° to 30° in each horizontal direction. The accuracy of saccades was unchanged by covering the strabismic eye, whilst covering the dominant eye resulted in decreased accuracy independent of visual acuity. van Leeuwen *et al.* concluded that saccades seem to be generated based on visual input from the dominant eye.

To guide saccades accurately, human adults learn rapidly to aim for the central position of the distribution of target positions studied; this is called the range effect. This means that saccades to targets in central locations are accurate, saccades to near targets lead to an overshoot and relatively distant targets lead to an undershoot. Five children with strabismus (including 4 without BSV) and 5 with normal BSV were studied by Kapoula and Bucci⁵ to determine how binocular vision affects the range response. They showed that range information is used by strabismic children as young as 5 years old to guide lateral saccades in the same way as

non-strabismic children. In view of the lack of binocular vision in 4 of the children tested this indicates that the range strategy can be driven by monocular visual input, particularly input from the dominant eye. This monocular input is also capable of guiding movements of both eyes regardless of their position in the orbit and regardless of whether they can or cannot use vision of the two eyes simultaneously.

Saccade velocity

Whilst measurement of saccade velocity is useful for differential diagnosis of innervational and mechanical disorders of motility⁹ there appears to be little evidence of any effect on velocity in concomitant strabismus.

de Faber *et al.*¹⁰ compared saccades of 8 strabismic subjects with amblyopia (1 esotropic and 7 exotropic) with those of 5 binocular controls using scleral coil recordings. The control group was found to have abducting saccades, which were greater in amplitude than adducting saccades, and the peak velocity of the abducting eye was, on average, 12° s⁻¹ higher than that of the adducting eye. In the strabismic group abducting saccades were also generally faster than adducting saccades. Towards the dominant eye they were faster in the dominant eye than the strabismic eye; at 60° stimulus amplitude the mean peak velocity difference was 66° s⁻¹. Towards the strabismic eye the velocity differences were less pronounced, with a mean difference of 25° s⁻¹ for a 60° stimulus amplitude.

For smaller-amplitude saccades up to 20°, Tian¹¹ demonstrated no clear difference in peak velocity amplitude between binocular control subjects and strabismic subjects with constant exotropia.

Bucci *et al.*¹² measured saccade velocity pre- and post-operatively in 8 children with concomitant strabismus, finding no change in the majority ($n=5$) after strabismus surgery. This finding is consistent with other reports exploring the change in velocity of saccades after small recessions of one muscle.^{13,14}

Metz⁹ suggested that identification of slipped muscle is possible by examining the saccadic peak velocity with reductions of peak velocity in the region of 40–50%. This was not the finding, however, in a recent study which aimed to detect slipped muscles after strabismus surgery.¹⁵ This study evaluated 4 adults with suspected long-standing slipped muscle due to a history of previous strabismus surgery and clinical evidence of restricted motility. Presence of slipped muscle was confirmed intra-operatively, but prior to this the saccade velocity (main sequence parameters) was measured. The analysis revealed normal saccadic peak velocities for muscles which had slipped up to 5 mm. One patient with a 10 mm slip of the medial rectus muscle showed saccades in the direction of the slipped muscle were markedly reduced and duration increased compared with saccades in the opposite direction. Hence it appears that slipped muscles that are of long standing cannot reliably be identified by saccadic peak velocity measures.

A consistent finding by Chen *et al.*¹⁵, however, was that cases of strabismus with previous corrective surgery had distorted saccadic velocity profiles such that instead of smooth symmetric profiles there may be, for example,

Table 1. Saccade disconjugacy in normal binocular vision and strabismus

Group	Author	Saccade amplitude (deg)	No. of subjects	Disconjugacy (deg)
Normal BSV	de Faber <i>et al.</i> ¹⁰	10–60	5	<–1
	Maxwell <i>et al.</i> ¹⁹	40	11	–0.3
	Kapoula <i>et al.</i> ¹⁸	5–20	3	<–1
Esotropia	Griffiths ⁶	8	5	<–0.4
	Maxwell <i>et al.</i> ¹⁹	40	11 amblyopes ≤ CF	≤+3.4
	Kapoula <i>et al.</i> ¹⁸	5–20	3 < 10 ^A 4 > 20 ^A	±1 +1.8 (up to +5 for large-amplitude saccades)
Exotropia	Griffiths ⁶	8	5	+0.4 (range –1.3 to +1.9)
	de Faber <i>et al.</i> ¹⁰	10–60	8	+5.6 (range +1 to +13.2) ^a +1.2 (range –1.26 to +10.4) ^b
	Griffiths ⁶	8	3	–0.7 (range –0.1 to –1.8)

Positive values represent convergent disconjugacy, negative values divergent disconjugacy.

BSV, binocular single vision; CF, count fingers.

^aData for saccades towards the dominant eye; ^bdata for saccades towards the strabismic/amblyopic eye.

two velocity peaks and distortion of the decelerating phase. These distortions were not related specifically to cases with slipped muscle and they persisted after correction of slipped muscles. The authors suggest that these distortions may develop as compensation for changes in, or damage to, the extraocular muscles.

Saccade conjugacy

Horizontal saccades are naturally disconjugate, with abducting saccades being faster and slightly larger than adducting saccades.^{10,16,17} This gives rise to brief relative divergence of the eyes following a saccade. In normal BSV this is small where typically, for horizontal saccades of < 20° from the primary position, the two eyes differ by < 0.5°.^{6,17} Table 1 gives an overview of the saccade disconjugacy reported in the literature in binocular vision and strabismus.

de Faber *et al.*¹⁰ compared the saccade conjugacy of 8 strabismic subjects with amblyopia (1 esotropic and 7 exotropic) and 5 binocular controls using scleral induction coil recordings. The control group was found to have abducting saccades greater in amplitude than adducting saccades, of < 1°. In the strabismic group, saccades towards the dominant eye were larger in the dominant eye with a > 1° difference between the two eyes. For a 60° stimulus amplitude the mean difference in saccade amplitude between the eyes was 5.6° with a range of 1° to 13°. Saccades towards the strabismic eye showed variable size differences, but were typically larger in the dominant eye. For a 60° stimulus amplitude the mean difference in saccade amplitude between the two eyes was 1.2° with a range of –1° to 10°. Hence saccades were more conjugate towards the strabismic eye than towards the dominant eye.

Kapoula *et al.*¹⁸ examined conjugacy of saccades measured using a Skalar infrared system in 3 non-strabismic subjects, 3 esotropes and 5 exotropes; the results are summarised in Table 1. Increased saccade disconjugacy in strabismus was attributed to weakness or absence of disconjugate adaptive mechanisms. The increase in disconjugacy in subjects with larger strabismus supports the idea of more severely deficient adaptive mechanisms due to the total lack of binocular interaction, compared with small-angled deviations where abnormal binocular interactions occur more frequently. Disconjugacy was seen in strabismics with and without amblyopia. The disconjugacy did vary

depending upon which eye was fixing, but no direct pattern was seen in the small-angled esotropes. However, in the large-angled esotropes saccades were always greater when fixing with the strabismic eye. This suggests, therefore, that binocular vision is important in maintaining binocular oculomotor coordination.

In contrast to the study by de Faber *et al.*¹⁰, who reported larger and more consistently divergent disconjugacy when the non-amblyopic, non-strabismic eye abducted, Kapoula *et al.*¹⁸ found no directional specificity in 7 esotropic subjects. Maxwell *et al.*¹⁹ studied conjugacy of saccades in strabismus with deep amblyopia in 10 subjects with esotropia and 1 with exotropia. They reported large amounts of disconjugacy, but did not show directional differences. The group studied by de Faber *et al.*¹⁰ were mainly exotropes, suggesting a possible difference in the behaviour of esotropes and exotropes.

Of interest is the finding by Griffiths⁶ that disconjugacy in 2 subjects with clinically demonstrable anomalous BSV was larger than in 4 of the 6 subjects with suppression and no demonstrable BSV. This does not, therefore, add support to the proposed hypothesis of Kapoula *et al.*¹⁸ that absence of binocular vision is the cause of disconjugate saccades.

Three reasons for the small divergent disconjugacy typically found in normal binocular subjects have been suggested: Kapoula *et al.*¹⁶ suggested that the high burst of saccadic pulse activity leads to disconnection of tonic vergence, thereby increasing divergence during a saccade. Zee *et al.*²⁰ proposed that it might be due to either a delay in arrival of pre-motor signals at the motor neurons of the medial rectus with respect to pre-motor signals to the lateral rectus, or differences in the mechanical properties of the medial and lateral recti.

The reasons for increased disconjugacy in strabismus are unclear. As amblyopia and strabismus frequently coexist, studies have not been conclusive regarding whether it is the presence of amblyopia or strabismus that leads to disconjugacy. Maxwell *et al.*¹⁹ studied subjects with strabismus and deep amblyopia. They demonstrated disconjugate saccades in all subjects, but significantly larger disconjugacy in the subjects with CF vision compared with the subject with 6/60, who had saccadic yoking almost as good as in the control subjects. They did not find any trend between the angle of strabismus and the degree of poor saccadic yoking. These authors, therefore, suggest that it is the deep

amblyopia, rather than strabismus, that gives rise to the observed disconjugacy. However Kapoula *et al.*¹⁸ found similar amounts of disconjugacy in esotropia without amblyopia, suggesting that strabismus alone is sufficient to disrupt saccade conjugacy. Kapoula *et al.*¹⁸ suggest that the disconjugacy may exist in strabismus without amblyopia due to a weakness or absence of disconjugate adaptive mechanisms.

Despite the reported disconjugacy of saccades in strabismus it is apparent that the amount of disconjugacy is consistent for each individual and the strabismic eye does not aimlessly wander. Consistent disconjugacy suggests that the same extra-foveal retinal area of the strabismic eye corresponding with the fovea of the fixing eye is constantly aimed towards the target.

Saccade adaptation

As described above, horizontal saccades are naturally disconjugate, with abducting saccades being faster and slightly larger than adducting saccades. Binocular vision requires images to fall on the foveae of each eye and therefore precise control over ocular alignment is essential. To maintain control, saccades are under an adaptive control system to compensate for short- or long-term changes to the visual system. Adaptive control monitors performance and adjusts parameters to improve accuracy and behaviour where required. As saccades are ballistic in nature and occur so quickly, ongoing feedback is not possible; therefore a learning process is involved in saccade adaptation.

Changes to the visual system, such as natural ageing, fatigue or disease processes, may lead to saccade adaptation to maintain comfortable BSV. Kommerell *et al.*²¹ noted that patients with acquired unilateral nerve palsy could adjust the amplitude of their saccades depending on which eye was forced to view. Abel *et al.*²² observed the adaptive changes in saccades in a patient who had a sudden-onset medial rectus paresis. They occluded the non-affected eye for 1 week, during which time the saccades of the paretic eye became larger in the appropriate direction. The largest change occurred during the first day, with changes on subsequent days being considerably smaller. An exponential curve fitted the time course of adaptation with a time constant of 0.85 days.

In controlled conditions Optican and Robinson²³ confirmed the existence of adaptive capabilities of the saccadic system in monkeys that had induced strabismus following muscle tenectomy. They were able to localise the adaptive controller to the vermis of the cerebellum. Studies of symmetric saccadic adaptive control have been carried out experimentally by techniques such as intra-saccadic step^{24,25} and electronic feedback systems.²⁶

Disconjugate adaptation in normal BSV

Saccades may also be adapted disconjugately, such that saccades become unequal in the two eyes. Lemij and Collewijn²⁷ investigated the time course of disconjugate saccade adaptation using short-term wear of anisometric spectacles. These are spectacle lenses that have different refractive powers resulting in visual images that

are differently sized, along both the horizontal and vertical axes, for the two eyes. They demonstrated in all 3 of their subjects that disconjugate saccades occurred with anisometropia ranging from 2 DS to 8 DS (dioptre spheres), with the adaptations almost complete within 1 hour. More recent studies^{28,29} showed that, under similar conditions where the image to one eye was magnified, disconjugacy occurred within a period of a few minutes and persisted under monocular viewing. This indicates the presence of a fast learning mechanism.

Disconjugate adaptation in microtropia

As disconjugate adaptation subserves binocular vision, Kapoula *et al.*³⁰ questioned whether foveal fusion is a prerequisite for achieving disconjugate adaptations. They studied 3 microstrabismic subjects who viewed a random dot pattern which was 10% larger in one eye. The subjects were instructed to make saccades to fixed points within the stimulus area. Within 40 seconds, horizontal saccades became larger in the eye viewing the larger stimulus by 4–10%. The induced saccade disconjugacy persisted under monocular viewing. This demonstrated that foveal fusion was not required for this mechanism and peripheral fusion was sufficient to drive adaptive changes.

Disconjugate adaptation in strabismus with no potential BSV

Bucci *et al.*³¹ examined the degree of binocular vision necessary to stimulate disconjugate adaptation. Using the same experimental set-up as described above³⁰ they concluded that subjects with peripheral binocular vision, and those with anomalous BSV, were able to demonstrate disconjugate changes in the binocular coordination of their saccades appropriate for the induced disparity. However, subjects without binocular vision made disconjugate changes to the amplitude of saccades but these were not in the direction appropriate for the induced disparity. This indicates that binocular vision, normal or anomalous, is required to simulate the appropriate mechanism of saccade adaptation. It is interesting to note that although subjects with no demonstrable binocular vision do not adapt normally to the stimulus, a mechanism exists to initiate an anomalous adaptation response.

In the experiment outlined above all subjects without potential BSV had their angle of deviation corrected, or partially corrected, with base-out prisms placed over the deviating eye. The reason stated for this was to render disparities similar in all subjects. This may have led to the anomalous responses found in the larger-angled strabismus with no demonstrable binocular vision, as points stimulated in each eye were significantly altered compared with those normally stimulated without correction of the deviation.

Griffiths^{6,32} used an electronic open-loop feedback system applied to one eye to induce large saccade disconjugacy in normal BSV. Under the same conditions 5 of 6 adults with strabismus (without prismatic correction) demonstrated disconjugate changes, showing that clinically demonstrable binocular vision is not required for disconjugate saccade adaptation. Three

subjects with manifest strabismus and no potential BSV demonstrated a rapid disconjugate adaptation of saccades in an appropriate direction of similar size and time scale to subjects with normal BSV. Two subjects (1 esotropia and 1 exotropia and no potential BSV) demonstrated adaptations but in a direction inappropriate for the disparity. Visual acuity and size of strabismus did not appear to be significant factors in the type of response; however, those with early-onset strabismus prior to age 6 months did not demonstrate normal adaptation.

Demonstration of disconjugate saccade adaptation, in subjects with strabismus, suppression and no potential BSV, shows that despite lack of perception of the target in the strabismic eye it appears to contribute to saccade programming. This suggests that fusion is not necessary for activating the adaptive mechanism.

Saccade adaptation following strabismus surgery

Bucci *et al.*¹² examined the binocular coordination of saccades in children with moderate to large strabismus (22^A-46^A) and possible modifications of the coordination of saccades after strabismus surgery. Before surgery, the disconjugacy of saccades was larger than reported in normal children of a similar age. Following surgery the disconjugacy of saccades was significantly reduced and there was less variability in the sign of the disconjugacy (convergent or divergent). It was proposed that this reduction in disconjugacy was mediated by central adaptive mechanisms giving a more efficient tuning of motor commands when the two eyes are aligned even in the absence of demonstrable binocular vision.

Bucci *et al.*¹² also examined the amplitude of post-saccadic drift (over the period after the offset of the primary saccade until the onset of a corrective saccade) to determine the quality of binocular fixational stability pre- and post-operatively. The surgery was found to have no effect on post-saccadic drift. The two findings in this study suggest, therefore, that the binocular coordination of the saccade and the binocular coordination of the drift are controlled by separate mechanisms. And whilst fusion is not required for adaptations to binocular coordination of the saccade, it seems that fusion may be required for binocular coordination of post-saccadic drift.

Summary

Despite misalignment and lack of clinically demonstrable binocular vision in concomitant strabismus, saccadic performance is relatively unaffected. Saccade latency, accuracy and peak velocity are, however, considerably affected when strabismus is associated with amblyopia. It is apparent that although saccades are more disconjugate in the presence of strabismus than in normal binocular individuals, the disconjugacy is consistent and the eyes behave as a yoked pair. Evidence from experimental work on saccade adaptation suggests also that even in the presence of pathological suppression, input from the strabismic eye leads to adaptation and affects saccade generation.

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