SACCADES IN THE ABSENCE OF BINOCULAR VISION

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NO PORTION OF THIS WORK REFERRED TO IN THIS THESIS HAS BEEN SUBMITTED IN SUPPORT OF AN APPLICATION FOR ANOTHER DEGREE OR QUALIFICATION OF THIS OR ANY OTHER UNIVERSITY OR INSTITUTE OF LEARNING

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Abstract

The mechanism of suppression in strabismus is unclear and contribution of the suppressing eye to the generation of eye movements has received little attention. A series of nine experiments tested how the strabismic eye contributes to saccade generation in the presence of suppression and also considered the effect of the strabismic eye in the presence of abnormal retinal correspondence (ARC). These data were compared with data from subjects with normal binocular single vision (BSV).

Chapters 2 and 3 describe the equipment, laboratory set-up and testing of the equipment used in the thesis for measuring eye movements, Skalar IRIS 6500 infrared limbal tracker, and presenting stimuli to each eye separately. The design of a novel method for dissociation of the eyes using four liquid crystal polymer shutters is presented.

Chapter 4 compares the characteristics of saccades made by subjects with normal BSV (n=5) and strabismus (n=8). The effect of distractors on saccades is explored in Chapter 5 in subjects with normal BSV (n=5). The experiment documents the distractor effect produced in the described laboratory set-up, and compares it with that previously reported by Walker et al (1997). This is investigated further by comparing the effect of distractor presentations to the dominant eye, non-dominant eye or both eyes. There was no difference in the effect on saccade latency or gain with distractors presented to the dominant or non-dominant eye. The effect of binocular distractors on saccade gain was greater than monocular presentations.

Chapter 6 repeats the experiment of Chapter 5 in subjects with constant strabismus and suppression (n=6) and constant strabismus with ARC (n=2) and found that distractors in the strabismic eye did affect saccades however the response differed from normal BSV. This was true even though it was shown that the distractor was not perceived by the strabismic eye.

Chapter 7 investigates the influence of the central fixation target in the strabismic eye on saccade generation by inducing disconjugate saccade adaptation in subjects with normal BSV (n=8) and constant strabismus and suppression (n=6). The findings were that in the presence of suppression, disconjugate adaptation similar to that in normal BSV was possible.

The conclusion of this thesis is to suggest that information from the suppressed eye is available to the saccadic system by either a sub-cortical pathway or processed cortically without conscious awareness.

Glossary of abbreviations

ARC	abnormal retinal correspondence
BSV	binocular single vision
DS	dioptre spheres
ERG	electroretinogram
EOG	electro-oculogram
ET	esotropia
FEF	frontal eye fields
IML	internal medullary lamina of the thalamus
LCP	liquid crystal polymer
LGB	lateral geniculate body
LIP	lateral intraparietal area of the posterior parietal cortex
LS	lateral supersylvian area
MLF	medial longitudinal fasciculus
NRC	normal retinal correspondence
ODC	ocular dominance column
OKR	optokinetic response
PPRF	paramedian pontine reticular formation
RiMLF	rostral interstitial nucleus of the medial longitudinal fasciculus
SC	superior colliculus
SEF	supplementary eye fields
SNpr	substantia nigra pars reticular
V1	striate cortex or visual cortex
V2	area of extrastriate cortex - secondary visual cortex
V3	area of extrastriate cortex in magnocellular pathway
V4	area of extrastriate cortex in parvocellular pathway: 'colour centre'
V5	area of extrastriate cortex responsible for motion detection also known as mediotemporal cortex or MT
VEP	visually evoked potential
VOR	vestibulo-ocular reflex
XT	exotropia

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Chapter 1

Introduction

This thesis investigates the role of binocular vision and the effects of strabismus, a condition when binocular vision is absent or abnormal, on saccadic eye movement characteristics and planning. This chapter reviews the literature, which motivated this study, and begins with an outline of saccade characteristics and the neural generation of saccades. The second part of the chapter considers binocular vision and strabismus with emphasis on the adaptations to strabismus. Finally the aims of the thesis are formulated.

1.1 Eye movements

Eye movements enhance visual function and require both sensory and motor function to have maximal effect. The study of eye movements allows the investigation, localisation and treatment of neurological disease, but also allows investigation into the mechanism of neurological processing. Eye movements can be classified into five main groups (Dodge, 1903), all having differing functions, which are summarised in Table 1.1.

Type of Eye Movement	Function
Vestibular	To minimise retinal image movement during brief head movements
Optokinetic	To hold images steady on the retina during sustained head movement
Smooth pursuit	To hold images of a moving target on the fovea
Saccades	To bring the object of interest onto the fovea
Vergence	To move the eyes in opposite directions to allow images of single objects at any distance to be placed on both foveae

Table 1.1: Classification of eye movements.

1.1.1 Saccades

Saccades are rapid eye movements used to redirect the foveae from one object to another. They have an abrupt onset of movement due to an extremely high initial acceleration of up to $30000°s^{-2}$ and have a peak velocity that increases proportionally with saccade amplitude up to a maximum of approximately $600°s^{-1}$ (Becker, 1989).

They may be voluntary or involuntary in nature, may be evoked by visual, vestibular or other sensory stimuli and may be directed to a specific target (goal-directed saccades) or used to reset the eyes (re-orientating saccades).

Becker's classification of saccades highlights the conditions under which saccades may be initiated dividing them into two main types:

- Goal-directed saccades are used to move the fovea onto a specific point in the visual world and are divided as follows: re-fixation saccades, which direct the eye to selected objects within the visual environment; scanning saccades, used to explore the visual environment attracted to salient features; tracking saccades, which result as a reflex movement evoked by sudden changes in the extrafoveal visual field; and catch-up saccades used to re-fixate moving targets when smooth pursuit is insufficient.

- Re-orientating saccades are not aimed at specific targets but bring invisible parts of the visual world into central visual field. Becker (1989) divides them as follows: fast phase of the vestibular ocular reflex (VOR), used to reset the eyes within the orbit following a vestibularly evoked compensatory movement in the opposite direction; fast phase of the optokinetic response (OKR), used to reset the eyes within the orbit following a visually evoked compensatory movement in the opposite direction; and micro-saccades which are small randomly directed saccades which interrupt fixation.

To generate this fast eye movement an innervational pattern, described as the 'pulse' and 'step', is sent to the extraocular muscles from the brainstem (Robinson, 1964). The pulse is a short burst of activity, which drives the eyes at high velocity against the viscous properties of the orbital contents. The strength and duration of the pulse determines the amplitude of the saccade. The step is an increase in activity to hold the eye in the desired position preventing a return to primary position. The pulse is generated in pre-motor cells of the brainstem in an area referred to as the 'pulse generator'. The size of the step signal is derived through integration of the pulse activity by a structure known as the neural integrator (Skavenski & Robinson, 1973; Arnold & Robinson, 1997). The neural integrator (see section 1.2.5) operates via connections between various structures within the brainstem and cerebellum, (Leigh and Zee, 1999).

1.1.1.1 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 200ms (Leigh & Zee, 1999; Becker, 1991). The latencies of individual saccades do not have a normal distribution around a mean of 200ms, however, the inverse of latency (promptness) is usually normally distributed (Carpenter, 1981). Multi-modal distributions may occur when the stimulus conditions are stable and controlled. Four separate modes have been identified (Boch & Fischer, 1986; Fischer & Ramsperger, 1986; Fischer, 1987) as follows: long latency regular saccades with latency in the region of 230ms; short latency regular saccades with latency of 150-200ms; express saccades with latencies of 90-130ms; anticipatory saccades with latencies of <80ms. Saccadic latency can be affected significantly by the nature of stimulus and experimental conditions.

The effect of target eccentricity on saccade latency is inconsistently reported. A summary of findings can be seen in Table 1.2. Wyman and Steinman (1973) demonstrated in two subjects, that saccade latency decreases with increasing target step size. From Table 1.2 it is apparent that most laboratories report highly increased saccade latencies (maximum 150ms increase) for eccentricities of <0.5°, with no significant differences for moderate eccentricities (1-15°). Large saccades, between 20° and 60°, begin to show a small increase in latency in the region of 20ms.

The luminance of the target has been shown to affect saccade latency such that it decreases at a negatively accelerated rate, by approximately 15ms per logarithmic unit of luminance increment above foveal threshold (Wheeless, Cohen & Boynton, 1967). Latency is also increased with reducing target contrast (Becker, 1991).

Source	Effect of saccade amplitude on saccade latency
Frost & Pöppel (1976)	No effect *3 subjects, range of eccentricity 5° - 45°*
Bartz (1962)	Increasing latency with target eccentricity. *3 subjects, range of eccentricity 2.5° - 40°* *subjects required to identify type of target verbally - time taken to 'see' and make saccade not just time to make saccade*
Wyman & Steinman (1973)	Decrease in latency with increasing target step size. Large increase of up to 150ms for very small target steps of 0.1° *2 subjects, range of eccentricity 0.05° - 0.5°*
Pirozzolo & Hansch (1981)	Increase for small saccades (2°-5°) and large saccades (15°) *12 elderly subjects, range of eccentricity 2° - 15°*
Findlay (1983)	Not affected between 1° and 15° for horizontal saccades *Conclusions from review of several studies*
Kapoula (1984)	Longer latency for 10° saccades than 3° saccades
Becker (1989)	Total increase of 20ms to 30ms as the target amplitude increased from 5° to 60° *No details of paradigm, subjects or data analysis*

Table 1.2: Summary of reported effects of target eccentricity on saccade latency for horizontal saccades.

Manipulation of the disappearance of the central fixation point in relation to the onset of the target influences saccade latency. Removal of the fixation point for a period of time prior to the onset of the target reduces saccade latency (gap paradigm), whereas if the extinction of the fixation point is delayed with respect to the onset of the new target then saccade latency increases (overlap paradigm) (Saslow, 1967). Saslow demonstrated that latency decreased by a maximum of 150ms as the gap increased up to 200ms and latency increased by a maximum of 50ms under overlap conditions up to 100ms (see Figure 1.1). Under gap conditions the number of short latency, express saccades increases (Fischer & Ramsperger, 1984). A neurological mechanism for the gap and overlap effects has been attributed to the cells of the rostral superior colliculus (SC), which are active during fixation and deactivated during saccades (Munoz & Wurtz, 1993a).

Visual attention has been shown to play a role in the occurrence of express saccades. Mayfrank, Mobashery, Kimmig and Fischer (1986) have shown that using identical fixation points and targets, the instruction to 'attentively fixate the fixation target' reduced the number of express saccades. Whereas the instruction to 'keep your eyes on the fixation target, but shift your attention to a peripheral point', gave rise to an increase in express saccades. This suggests that presence or absence of a fixation target cannot

account for the occurrence of express saccades. It seems that directed visual attention prevents the oculomotor system from producing express saccades.

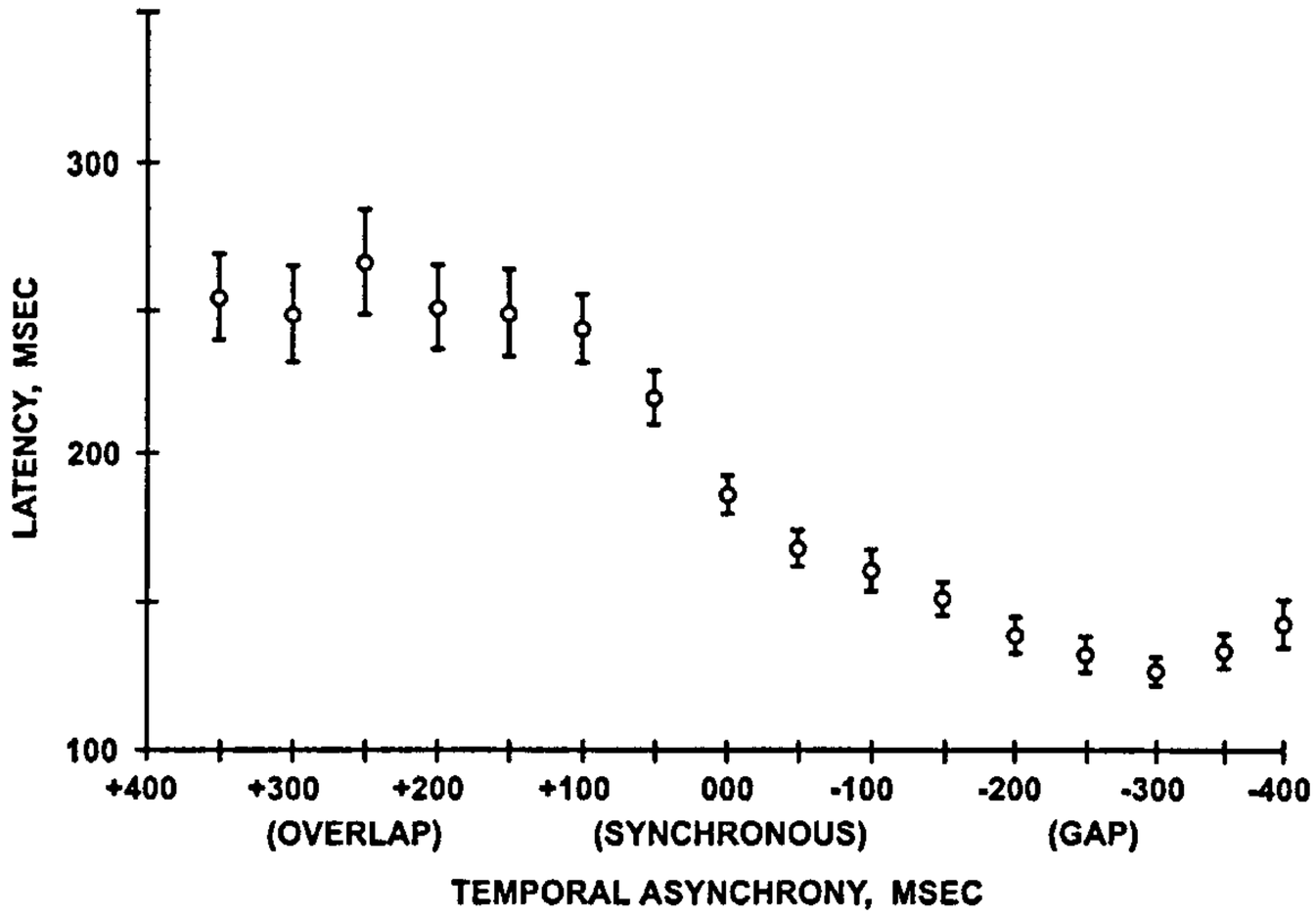

Figure 1.1: Saccade latency as a function of target asynchrony. Each data point represents the mean of 100 saccades ±2 standard errors. From Saslow, 1967.

A warning by any sensory stimulus prior to the saccade stimulus reduces saccade latency. In a series of step stimuli, with fixation periods between steps of <3s, the previous step gives warning of the next step, hence reducing latency as the pattern is established. Evenly distributed step intervals between 350 and 650ms have been shown to reduce saccade latency such that it decreases with decreasing step interval (Findlay, 1981). Anticipatory saccades may occur if the target is predictable, for example repeatedly from one position to another, in which case the eye movement may precede the stimulus. Saccades with latencies up to 80ms are also considered anticipatory, as this time period is required for the brain to process the visual signals and plan the motor response (Becker, 1991). This was adopted as the criteria in this thesis, saccades with latencies less than 80ms were excluded from analysis.

The latency of saccades can be altered by the presence of a peripheral target, or distractor. This is of particular interest in this thesis as Experiment 4 of Chapter 5 and Experiments 5 and 8 of Chapter 6 study the effect of distractors on saccade latency and accuracy. Lévy-Schoen (1969) showed that saccade latency was increased by 40ms when a distractor appeared simultaneously in a mirror symmetric position of the contralateral hemifield to the stimulus. If the distractor appeared adjacent to the saccade stimulus in the same hemifield the latency was unaffected but the accuracy was compromised. This phenomenon agrees with subsequent studies in which, when two

targets appear, the saccade becomes directed to a point between the targets, termed the 'global effect', (Findlay, 1982; Deubel, Wolf & Hauske, 1984) (see the remote distractor effect, Section 1.1.2).

1.1.1.2 Saccade peak velocity

Saccadic peak velocity increases with saccade amplitude, typically saturating for saccades of approximately 50°. The normal values for this relationship fall within a single smooth curve known as the main sequence (Bahill, Clark & Stark, 1975). Figure 1.2 shows a typical main sequence. The peak velocity tends to peak at around $500°s^{-1}$, however variations occur in normal subjects from 350 to 700ms. The velocity profile of large saccades is skewed such that there is an initial rapid acceleration to reach the peak velocity, followed by a slower deceleration. Small saccades, in contrast, show a more symmetric profile with the acceleration and deceleration periods being almost symmetrical.

The duration and peak velocity of saccades is dependent upon the position of the eye within the orbit due to mechanical factors. Three main positions within the orbit can be described; centrifugal; centripetal; and symmetrical. Centrifugal saccades begin at the midline and are directed eccentrically, centripetal saccades commence eccentrically and end at the midline and symmetric saccades cross the midline. Saccadic velocities for these three positions are not significantly different for saccades of <15°, however for 30° saccades, reductions of around $90°s^{-1}$ for centripetal saccades, compared to centrifugal saccades, have been reported (Hyde, 1959; Becker, 1989).

Abducting and adducting saccades[1] also differ in duration, acceleration and peak velocity. Conflicting results have been reported which appear to result from the method of recording. EOG recordings have consistently shown that the adducting eye is faster than the abducting eye (Boghen, Troost, Daroff, Dell'Osso & Birkett, 1974; Bird & Leach, 1976). Whereas with infrared recordings the abducting eye have been shown to accelerate faster and achieve a higher peak velocity than an adducting eye (Fricker & Sanders, 1975; Hallett & Adams, 1980). Preliminary observations by Becker (1989) showed that for the same saccades recorded with the EOG and search-coil methods the finding of faster adducting saccades with EOG was not present with the search-coil. The difference in peak velocity, abducting saccades faster than adducting saccades, for moderate sized saccades has been shown to be in the region of 20ms (Becker, 1989).

[1] Abducting saccades are directed temporally, adducting saccades are directed nasally.

Attentional factors, fatigue (Becker, 1989) and drugs that reduce alertness (Jürgens, Becker & Kornhuber, 1981) have been shown to reduce saccade peak velocity. Memory guided saccades (Becker & Fuchs, 1969) and anti-saccades (Hallett, 1978), in which the subject is instructed to look in an equal and opposite direction to the target, showed reduced peak velocity compared to saccades made to a permanently visible target.

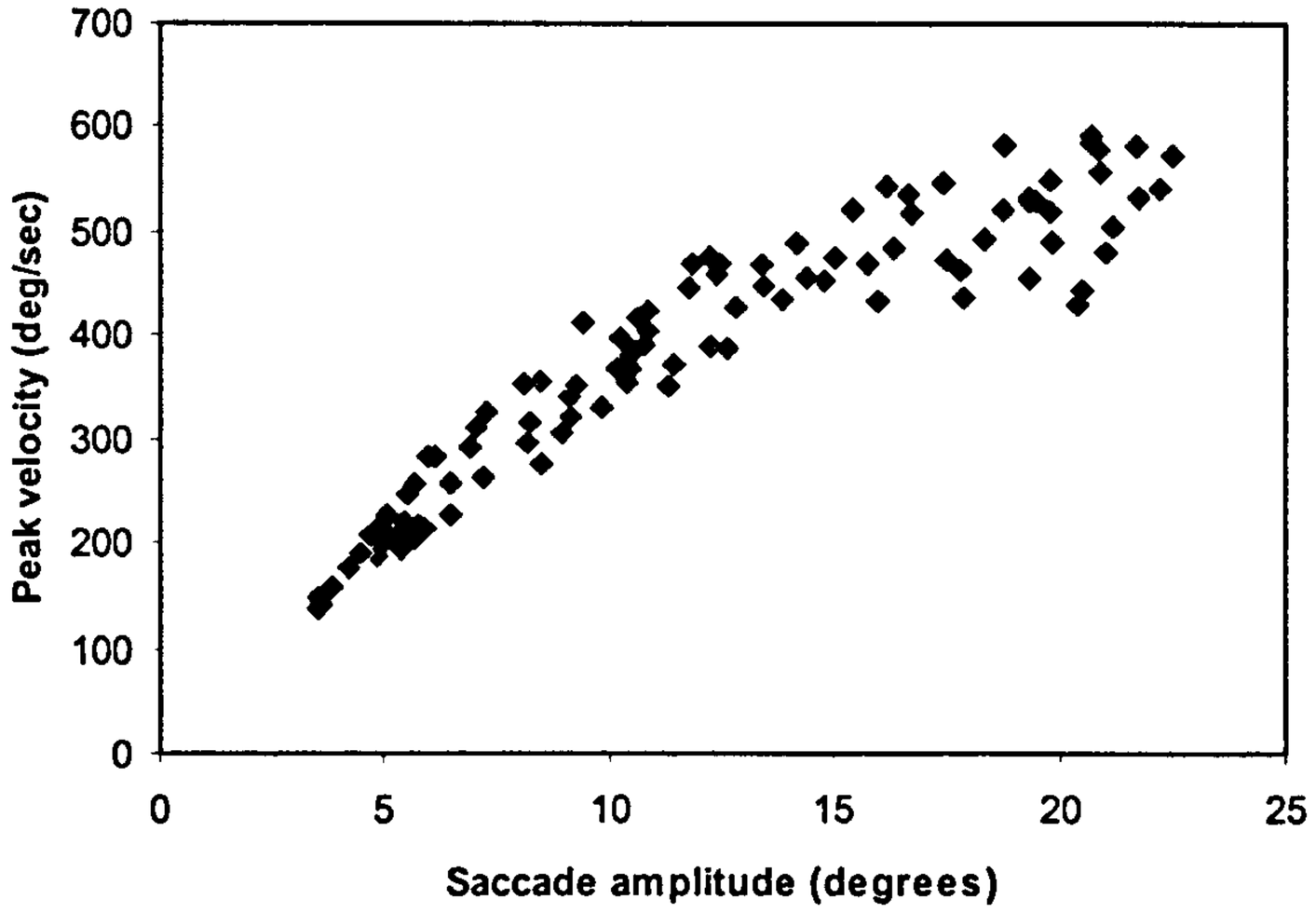

Figure 1.2: The relationship of saccade amplitude to peak velocity. This relationship is called the main sequence. Data collected by H. Griffiths.

1.1.1.3 Saccade accuracy

Due to the long processing time, compared to the time it takes to execute them, saccades are said to be ballistic movements, which once started cannot be influenced. The perfect saccade would rapidly reach the target and stop abruptly without error. This, however, does not always occur and is known as dysmetria, leading to the necessity for corrective movements following the initial saccade to align the fovea to the target. The corrective movements may consist of a second corrective saccade or the eye may slowly glide onto the target, known as a glissade. The task (Lemij & Collewijn, 1989), stimulus size (Kowler & Blaser, 1995), stimulus brightness (Doma & Hallett, 1988) and the background around the target all influence the amount of dysmetria. Saccades may undershoot the target, referred to as hypometric saccades, or overshoot the target, known as hypermetric saccades. Inaccurate saccades result from two types of error:

1. **Pulse - step mismatch**
   Incorrect pulse size with correct step, the eye therefore gradually creeps onto target.
2. **Step size error**
   Correct pulse with incorrect step size, where the eye precisely reaches the target, but cannot be maintained at this position.

Often a combination of these two errors occurs resulting in a combination of glissades and corrective saccades (see Figure 1.3). Evidence gained from lesions in monkeys shows that the cerebellum is involved in control of pulse and step generation to avoid mismatches (Ritchie, 1976; Optican & Robinson, 1980). The cerebellar vermis controls pulse size and the flocculus controls the pulse step match (Optican, 1980).

Methods of measuring accuracy are as follows:

- Frequency of occurrence, which considers the percentage of under and overshooting saccades.
- Error amplitude, which equals the difference between the target distance and the saccade amplitude. Negative values indicate an overshoot, positive values indicate an undershoot of saccades and zero indicates a precise saccade reaching the target.
- Saccade gain, which is the saccade amplitude divided by the target distance. A value of 1 represents a saccade that is on target; a value <1 equals an undershooting saccade and a value >1 equals an overshooting saccade. This method is used in this present study.

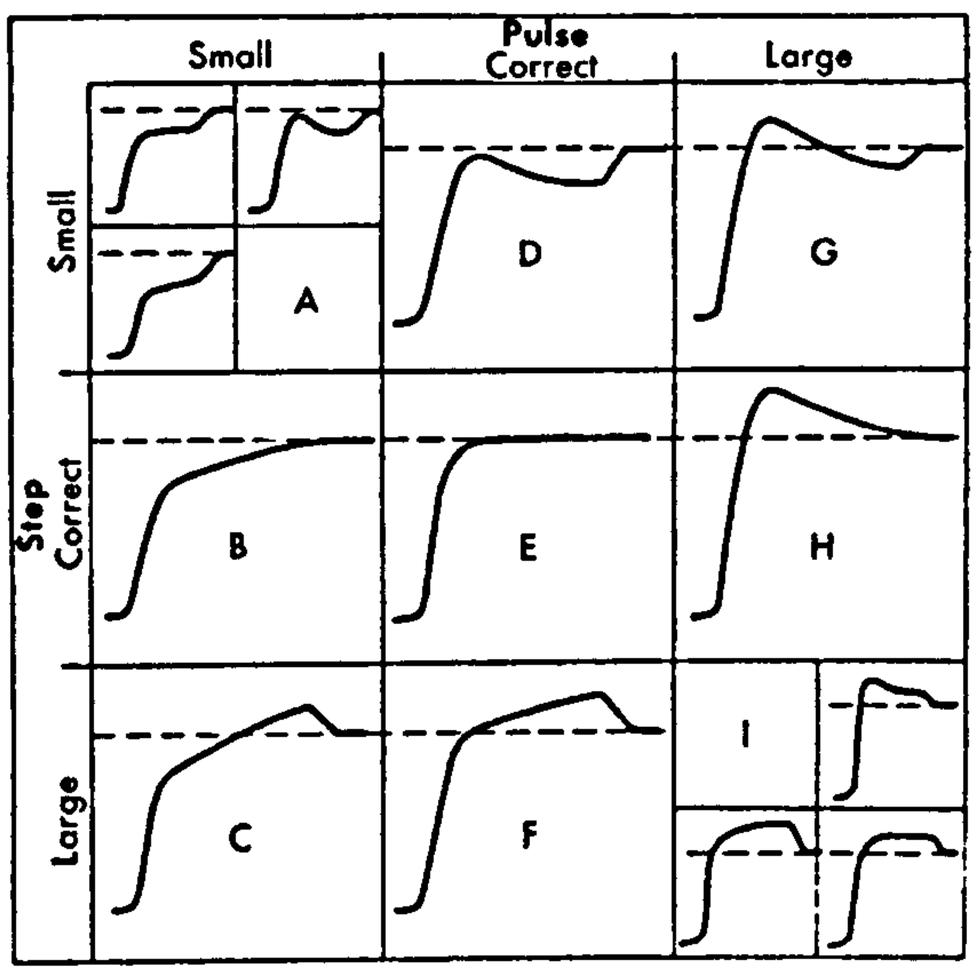

Figure 1.3: Pulse-step mismatch. Pulse and step components of saccadic control signal can be mismatched as shown. When the step is correct but the pulse is too large (H), a glissadic overshoot is generated. When the pulse is too small (B), the resulting saccade stops short of its final position and a glissade finishes the movement. When the step component is incorrect the saccade moves the eye to an off-target position, where it remains until visual feedback instigates corrective saccade either forward to the target (D) or backwards to it (F). When both pulse and step are too large (I) or too small (A), the primary saccade may be followed by rightward glissade, leftward glissade, or no glissade at all, depending of relative sizes of components. Broken line through each trajectory marks target. (From Bahill & Stark, 1979)

Most saccades slightly undershoot the target requiring one or two corrective saccades, the amount of undershoot is usually around 10% of the total target amplitude (Barnes & Gresty, 1973). Whether undershoots occur deliberately in larger saccades, to produce the quickest way of getting the eye on target, is debated. In the dark the main saccade is often followed by a secondary saccade in the same direction and of approximately 10% of the amplitude of the main saccade (Becker & Fuchs, 1969). This has raised the hypothesis that the corrective saccade is part of a predetermined two-step sequence and not elicited by visual feedback of an unforeseen error. However, the size of the corrective saccade highly correlates to the error, even when the target position is altered just after initiation of the main saccade, indicating visual input determining the size of the required corrective saccade (Becker & Fuchs, 1969; Deubel, Wolf & Hauske, 1982). Henson (1978) showed that if saccades were made to consistently overshoot by displacing the target during the saccade, the saccadic system adapted until a 10% undershoot was re-established.

Other studies however have not reported consistent undershooting of the target. As can be seen in Figure 1.4 the percentage of undershooting saccades has been shown to increase, and overshooting saccades decrease, as the stimulus amplitude increases (Bartz, 1967; Becker, 1972). Kapoula and Robinson (1986) showed that the range of target positions used in an experimental session influenced the accuracy of saccades, such that distances at the upper end of the range are underestimated and those at the lower end of the range overestimated, regardless of the absolute amplitude.

Undershoots are more common in centrifugal than centripetal saccades and overshoots are more common in centripetal than centrifugal saccades (Becker, 1989). Collewijn, Erkelens and Steinman (1988) have shown that the presence of constantly visible targets reduces the error considerably (see Figure 1.4). The presence of other objects close to the target alters the accuracy of the saccade, such that the saccade relates to a spatial average of the target and non-target (Coren & Hoenig, 1972) termed the Global effect (Findlay, 1982). The saccade has been shown to land nearer to the stimulus with more salient properties (Findlay, 1982).

Saccade accuracy is reduced if, following the appearance of the target, saccade latency is less than 80ms (Findlay, 1981). Saccades of short latency are termed anticipatory or predictive saccades and have also been shown to have different dynamics to saccades of longer latencies, i.e. >80ms (Bronstein & Kennard, 1987).

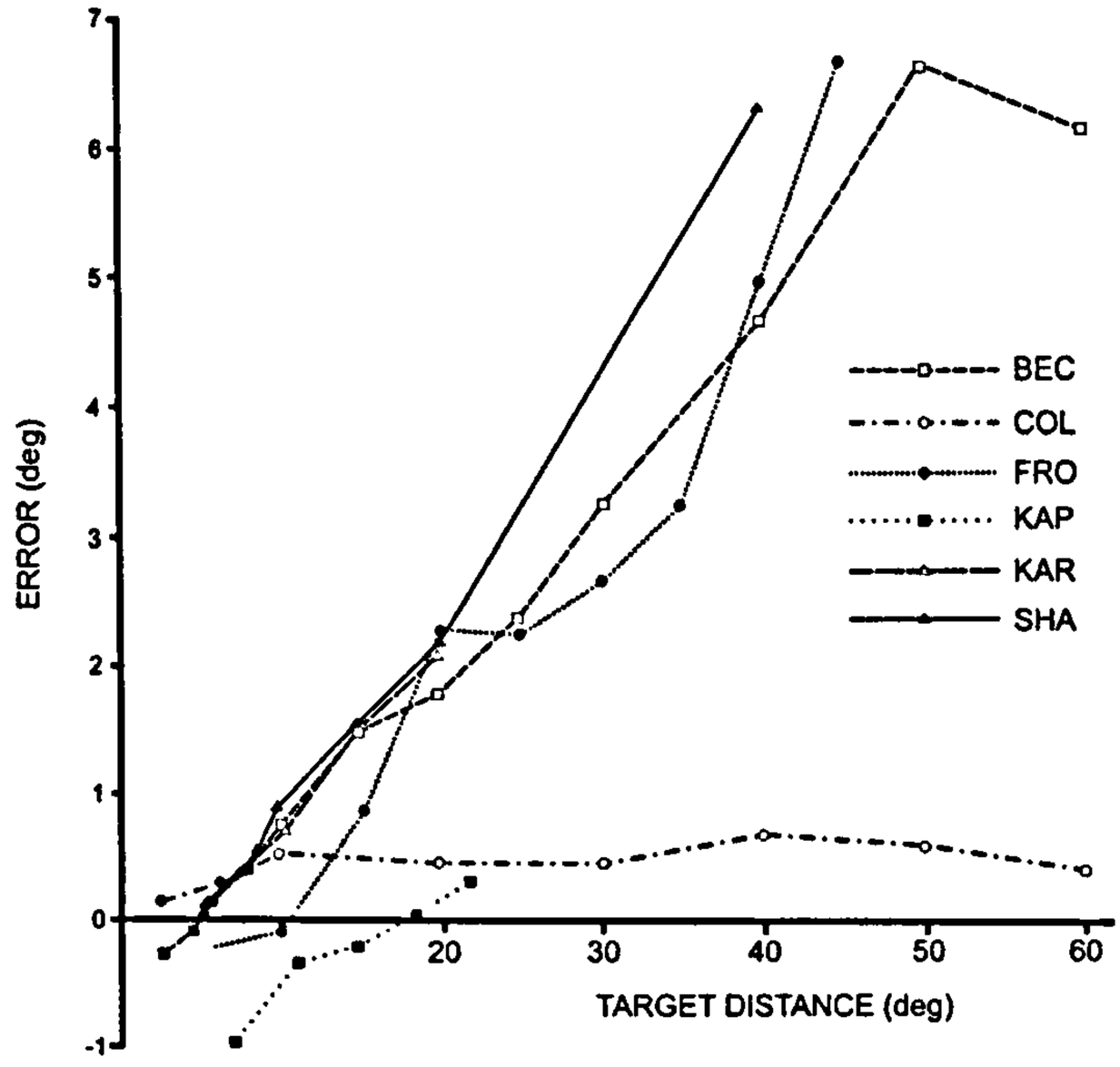

Figure 1.4: Saccade accuracy as a function of eccentricity. Positive values represent an undershoot of the target, negative values an overshoot. Data accumulated from various authors as follows: BEC, Becker, 1975; COL, Collewijn et al, 1988; FRO, Frost & Pöppel, 1976; KAP, Kapoula, 1985; KAR, Kapoula & Robinson, 1986; SHA, Sharpe & Zackon, 1987. (From Becker, 1991.)

1.1.2 The remote distractor effect

This thesis will use the remote distractor effect in Experiment 4 of Chapter 5 and Experiments 5 and 8 of Chapter 6.

A distractor is a stimulus presented at non-target locations within the visual field, usually simultaneously with presentation of the target. As described in Section 1.1.1.1 simultaneous presentation of a target and distractor in mirror symmetrical locations has been shown to increase saccade latency by approximately 40ms. Whereas, if the target and distractor are presented in close proximity saccade latency is not affected but accuracy is compromised (Lévy-Schoen, 1969).

Weber and Fischer (1994) have examined the effects of distractors, in normal subjects, on express saccades. They presented saccadic stimuli on the horizontal axis in which half the trials had simultaneous distractors in the contralateral hemifield and half were presented without distractors. There was a significant difference in the saccadic latency when the distractor was present and express saccades were absent. This was not thought to be an increase in latency due to the time taken to decide which was the actual target,

as the subjects were told in advance which side the target would be presented to. They also examined the effect of variable sized distractors with the conclusion that smaller distractors (0.1° x 0.1°) had less effect on latency than larger distractors (0.4° x 0.4°). The eccentricity of the distractor was also significant with the distractor having more effect when situated 4° from the midline compared to 12°. The effect of ipsilateral distractors was also investigated and found to reduce the number of express saccades when presented close to the original fixation region the so-called 'dead zone' (Weber, Aiple, Fischer & Latanov, 1992). The experiments concerned with contralateral distractors used distractors consisting of a vertical strip of three bars, whereas the ipsilateral distractor trials used a vertical strip of 23 bars. This discrepancy therefore does not allow a complete picture of the distractor effect.

Walker, Kentridge and Findlay (1995) have shown that the timing of the appearance of the distractor was a significant factor. Distractors presented simultaneously with the stimulus, but in the contralateral hemifield, increased the saccade latency by 20 to 30ms. Latency was also increased if the distractor preceded the target by an interval of <100ms and the reverse occurred with distractors appearing between 100ms and 250ms before the saccadic stimulus, where the saccade latency reduced compared to the no distractor condition. The distractor appearing >100ms in advance of the stimulus was thought to act as a warning to the appearance of the stimulus.

Walker, Deubel, Schneider and Findlay (1997) considered the distractor effect in more detail (this study was replicated in Chapter 5). A consistent distractor size was used and the location of the distractor was presented at several locations in both the contralateral and ipsilateral hemifields. The study reports data collected from six visually normal subjects with stimuli presented on a 21-inch colour monitor. Eye movements were recorded using a Dual-Purkinje eye tracker. The target used to stimulate visually directed saccades was a diagonal cross of length 0.19° and the distractor consisted of a 0.53° circle. With the offset of the central fixation cross the target and distractor appeared simultaneously. Target and distractor positions were varied in four experiments to include horizontal and vertical meridians. The results demonstrated a reciprocal effect on saccade latency and accuracy depending on distractor location. Distractors presented within a window 20° around the target axis modulated amplitude, but did not influence latency. Distractors presented >20° from the target axis increased latency, but had no effect on amplitude (see Figure 1.5). The latency increase reached a peak with distractors at the fixation location.

The increase in saccade latency with distractors at the original fixation point has been explained as an increase in activity of the fixation cells in the rostral pole of the superior colliculus (see Section 1.2.3.1) (Doris & Munoz, 1995; Munoz & Wurtz, 1992, 1993a, b, 1995 a, b). These fixation cells show a tonic discharge during fixation and represent the central 2° of the visual field. Walker, Deubel, Schneider and Findlay (1997) suggested that the increased latency found with contralateral distractors up to 10° from fixation may be explained by the occurrence of fixation cells further from the fovea than the 2° region of the rostral pole. This is supported by the work of Gandi and Keller (1995) who reported neurons resembling fixation neurons in more caudal regions of the superior colliculus. These neurons extended to areas associated with saccades of 10° or less.

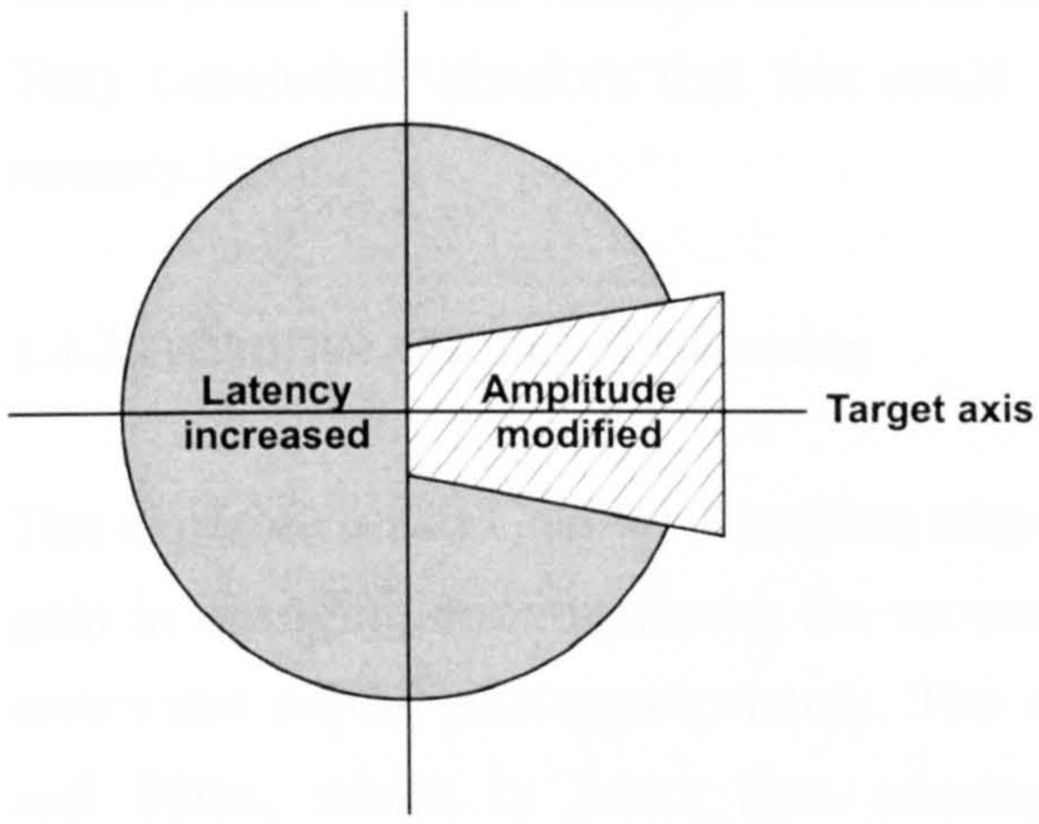

Figure 1.5: Schematic diagram of visual field illustrating the reciprocal effects on saccade latency and amplitude depending on distractor location. Distractors presented within a window of 20° around target axis modulated amplitude, but did not influence latency. Distractors presented away from target axis (>20°) increased latency, but had no effect on amplitude. (Walker et al, 1997).

Rafal, Smith, Krantz, Cohen and Brennan (1990) examined the latency of saccades made by hemianopic patients to stimuli presented in their intact visual field under conditions in which visual distractors appeared in their blind field. They found that saccade latency increased when distractors were presented in the blind field. A similar increase in latency could not be demonstrated in normal subjects. These findings were taken as showing that the distractor effect was specific to the oculomotor system and may be observed only when the cortical visual pathway is inoperative, suggesting that the sub-cortical visual pathway is responsible for the distractor effect. Walker, Mannan, Maurer, Pambakian and Kennard (2000), however, revealed no evidence of blindsight inhibitory effects in hemianopic subjects with cortical lesions. They concluded that the distractor effect was a normal characteristic of the saccadic system and may be related to the process of response competition involved in saccade target selection. This may be mediated by the deep colliculus, which depends on the corticotectal pathway for visual input.

These conflicting results have not been fully explained, however as noted by Findlay and Walker (1999) the control data of Rafel, Smith, Krantz, Cohen and Brennan (1990) does show a small latency increase for bilateral presentations. A possible explanation for differences in the hemianopic subjects may be variations in the extrastriate damage which produced the hemianopia (Walker, Mannan, Maurer, Pambakian & Kennard, 2000).

Patients with unilateral neglect typically have lesions of the right parietal lobe resulting in failure to respond to and lack of awareness of objects in the contralateral side to the lesion. Walker and Findlay (1996) studied saccades in two subjects with unilateral neglect without hemianopia. Presentation of bilateral targets at equal and opposite eccentricities did **not** result in increased saccade latencies as found in normal subjects. They concluded therefore that this could not be attributed to a lack of contralesional sensory input.

1.1.3 Adaptive control of saccades

The experiments in Chapter 7 involve adaptation of saccades. To obtain optimal saccade gain in changing circumstances, the saccadic system is under adaptive control to detect errors and adjust gain appropriately. The duration of a saccade is typically between 60 and 80ms, which is faster than sensory processing of visual information. Direct feedback during the saccade to improve accuracy is therefore not possible. Adaptive control systems are self-correcting, which continually monitor their own performance. In the event of under or overshooting the target, the system adjusts parameters to reduce the probability of such an error occurring again. This process is important for making long-term gradual changes, for example in ongoing growth development and ageing, but also in response to disease or injury affecting saccade parameters and dynamics.

Kommeral, Olivier and Theopold (1976) reported that patients with unilateral ocular motor nerve palsies could adjust the amplitude of saccades depending on which eye was forced to view. Abel, Schmidt, Dell'Osso and Daroff (1978) described the same response in a patient with partial third nerve palsy.

Experimental paradigms, which shift the target back towards its original location during the saccade (intrasaccadic step) have been used to study saccade adaptation. This leads to saccades, which initially overshoot the target, such that adaptive control is required to reduce the amplitude of saccades to improve accuracy.

1.1.3.1 Characteristics of adaptive control

Saccade adaptation is direction specific, such that modification of gain in one direction does not affect the gain of saccades in the opposite direction (Abel, Schmidt, Dell'Osso & Daroff, 1978; Deubel, Wolf & Hauske, 1986). This is desirable as it allows adaptation in one direction due to possible changes to a particular pairing of extraocular muscles without influencing the unaffected opposite direction.

Differences have been found in adaptive control requiring gain increases and gain decreases although these differences are debated. Miller, Anstis and Templeton, (1981) and Deubel, Wolf & Hauske, (1986) found that gain decreases occurred faster than gain increases. More specifically Miller, Anstis and Templeton, (1981) reported that gain decreases were 60% complete and gain increases only 25% complete over the same time scale. This was in contrast to Abel, Schmidt, Dell'Osso and Daroff, (1978) and Albano and King, (1989) who described faster adaptation for gain increasing adaptation. The main difference in the study by Albano and King, (1989) was that they produced saccade dysmetria by electronically adding or subtracting a fraction of the eye position signal to adjust the target position. This induced visuomotor errors proportional to saccade amplitude, therefore more closely mimicking naturally occurring saccadic dysmetria for the primary, as well as corrective, saccades.

The effect of saccade adaptation on saccade latency has been inconsistently reported. Straube, Fuchs, Usher and Robinson (1997) found increased latency of the primary saccade in two out of four monkeys studied, as did Takagi, Zee and Tamargo (1998), who reported a change in the distribution of latency in adaptive saccades due to the loss of express saccades.

1.1.3.2 Time course of adaptation

In both monkeys (Optican & Robinson, 1980) and humans (Kommerell, Olivier & Theopold, 1976; Abel, Schmidt, Dell'Osso & Daroff, 1978) muscle weakening has been shown to result in adaptive changes occurring slowly over a period of days. Fast adaptations, occurring within a few minutes (50 to 100 saccades), have been demonstrated experimentally using intrasaccadic target steps (Miller, Anstis & Templeton, 1981; Deubel, Wolf & Hauske, 1986) and electronic target feedback (Albano & King, 1989). This difference in the time course of adaptation suggests that two systems may exist; one for fast adaptation and one for slow adaptation.

It is possible that the fast adaptation seen in response to experimental conditions may not be a true adaptation of the oculomotor system and may therefore represent a conscious strategy by the observer in reaction to the stimulus. This however is not thought to be the case as the change in gain reported is gradual and follows an exponential time course (Deubel, Wolf & Hauske, 1986; Deubel, 1987). A conscious strategy to change the amplitude of saccades would be expected to occur abruptly.

1.1.3.3 Site of adaptive control

Patients with cerebellar degeneration have been shown to have saccade dysmetria suggesting involvement of the cerebellum in adaptive control (Dichgans & Jung, 1974; Zee, Yee, Cogan, Robinson & Engel, 1976). Further localisation to the vermis of the cerebellum has been found in monkeys (Optican & Robinson, 1980). This was concluded by unilateral surgical weakening of the lateral and medial recti, which resulted in adaptive compensation depending on which eye was forced to view over a period of a few days. However, following total cerebellectomies the saccadic system could not compensate for the muscle weaknesses. Furthermore, partial cerebellectomies of the vermis, paravermis, and fastigial nuclei eliminated adaptive control of the size of saccades but did not affect the step component.

To investigate the site of adaptation in human subjects Hopp and Fuchs (2002) adapted two types of saccade thought to be generated through different neuronal pathways. These were targeting saccades, having long latencies and thought to involve higher cortical processing, and express saccades, which have very short latencies, thought to be processed sub-cortically (i.e. early visual areas, the SC and the brainstem, Fischer & Weber, 1993). An experimental paradigm with an intrasaccadic target step backwards towards the initial fixation location was used. Gain was found to be adapted for both express and targeting saccades in similar proportions leading to the conclusion that adaptation occurs after the pathways generating these two types of saccade converge, i.e. at or below the SC.

It may be, therefore, that slow adaptation occurring naturally, for example due to disease or trauma, occurs in the cerebellum whereas fast adaptive changes found in response to an experimental intrasaccadic step result from a different pathway at or below the SC.

1.1.3.4 Disconjugate adaptation

Saccades may also be adapted disconjugately, such that saccades become unequal in the two eyes. This has typically been investigated using anisometropic lenses to magnify the image to one eye (Lemij & Collewijn, 1991; Kapoula, Eggert & Bucci, 1995; Van der Steen & Bruno, 1995). A review of literature relating to disconjugate adaptation in normal binocular single vision (BSV) and strabismus is given in Chapter 7. A novel method of inducing disconjugate adaptation is used in the experiments of that chapter in subjects with bifoveal BSV, and subjects with strabismus but no clinically demonstrable BSV.

1.2 Neurophysiology of saccadic eye movements

Experiments of Chapters 5, 6 and 7 investigate the generation of horizontal saccades in relation to presence or absence of binocular vision. Discussion of the results of these chapters considers cortical and sub-cortical areas involved in saccade generation. The visual pathways and the main areas involved in saccade generation are therefore summarised in the following sections.

Areas within both the cortex and sub-cortex are involved in the generation of saccades. Visual information from the retina reaches these structures via two visual pathways. The result is a pre-motor command signal to the oculomotor nuclei in the brainstem, which, in turn, leads to innervation creating contracture of the required extraocular muscles to execute the appropriate saccade.

1.2.1 Visual pathways

The majority of retinal ganglion cells project to the LGB. Nine other nuclei within the brain also receive retinal input (Hendrickson, Wilson & Toyne, 1970). Table 1.3 lists these nuclei and summarises the function of the fibres of each pathway. The two main pathways involved in binocular vision and saccadic eye movements are the retino-geniculo-cortical pathway and retino-collicular pathway (sub-cortical or tectal pathway). These pathways are shown in Figure 1.6 and will be briefly outlined below.

Nucleus	Function
Lateral geniculate body (retino-geniculo-cortical pathway)	Visual perception
Pregeniculate nucleus	Visual perception
Superior colliculus (retino-collicular pathway)	Control of eye movements
Pretectal nuclear complex	Control of pupillary responses
Suprachiasmatic nucleus	Control of diurnal rhythms & hormonal changes
Paraventricular nucleus	Neuroendocrine regulation
Supraoptic nucleus	Neuroendocrine regulation
Pulvinar	Saccadic suppression & attention See section 1.2.2.6
Accessory optic system	Optokinetic reflexes
Nucleus of the optic tract	Optokinetic reflexes

Table 1.3: Nuclei receiving projections from the retinal ganglion cells and their function. Adapted from Hendrickson, Wilson and Toyne, 1970.

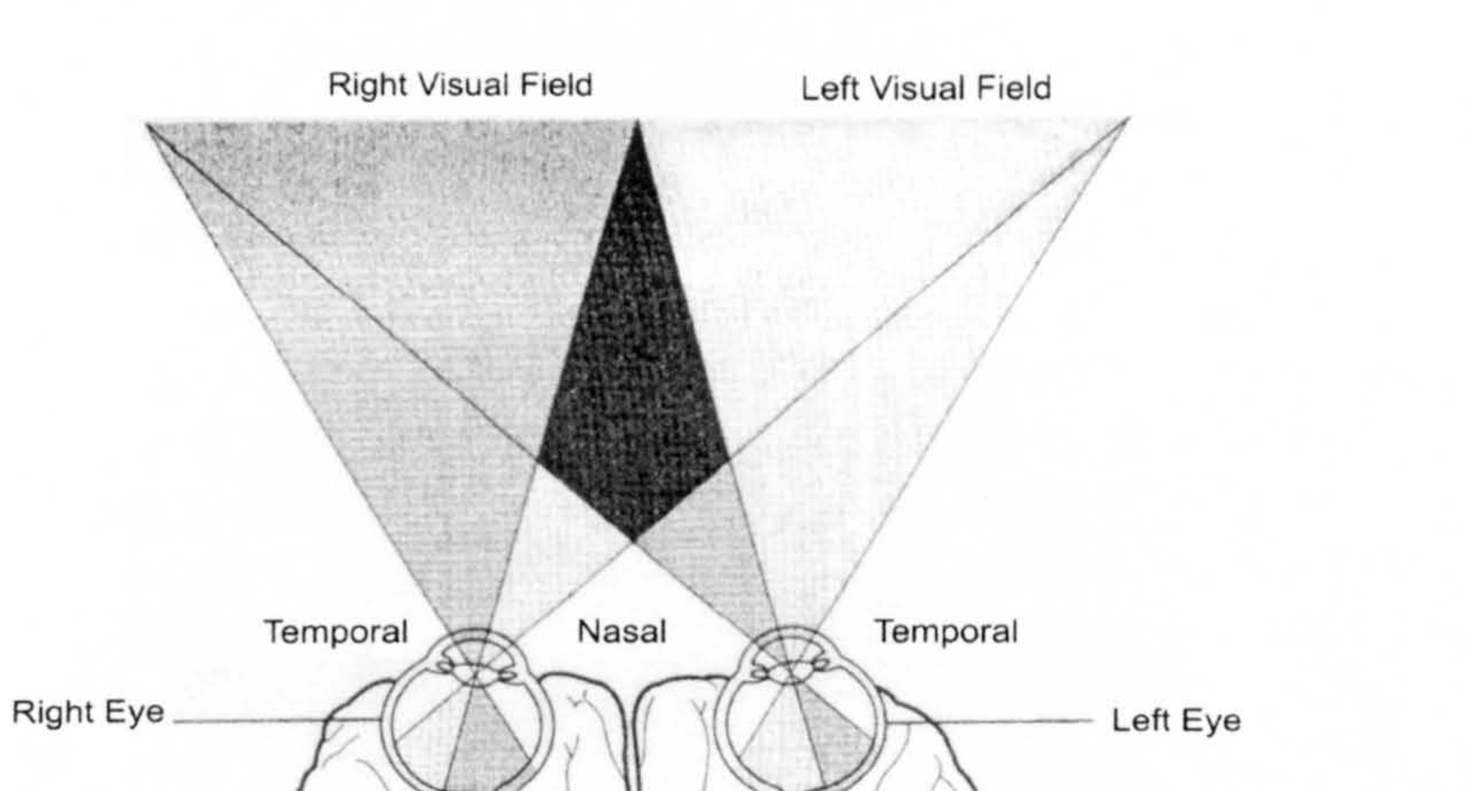

Figure 1.6: Schematic diagram of the visual pathway, viewed from below. The retino-geniculo-cortical pathway projects from the retina to the optic nerve, optic chiasm, optic tract, lateral geniculate body and optic radiations to V1. The retino-collicular pathway takes the same course up to the optic tract where it leaves to pass to the superior colliculus. Axons from nasal retina decussate at the chiasm, axons from temporal retina do not decussate and remain on the ipsilateral side. Stimuli in the left visual field are processed in the right cortex and right visual field in the left cortex. Adapted from Daw, 1995.

1.2.1.1 Retino-geniculo-cortical pathway

The retina is a thin layer of nervous tissue where vision begins with the capture of images focused by the optical media of the eye. The landmarks of the retina are the optic nerve, retinal blood vessels, area centralis, which includes the fovea and foveola, and the peripheral retina, which terminates at the ora serrata (see Figure 1.7).

The fovea is the point of fixation giving the highest level of visual acuity. It is situated in the central retina and defines the vertical division of the visual field splitting the retina into nasal and temporal halves. Objects in the temporal visual field are projected upon nasal retina and vice versa. Ganglion cells in the retina are the only cells that project from the eye to the brain. Ganglion cells located in the nasal retina, project to the contralateral side of the brain via the optic chiasm, whereas the temporal retina projects to the ipsilateral side. The ganglion cell axons terminate in the thalamic relay nucleus called the lateral geniculate body (LGB). From here the post-synaptic fibres pass in the optic radiations to the primary visual cortex, known as visual area 1 or V1. Visual perception occurs in V1 and in adjacent extrastriate areas. These associated visual areas have been named V2, V3, V4, V5 and V6.

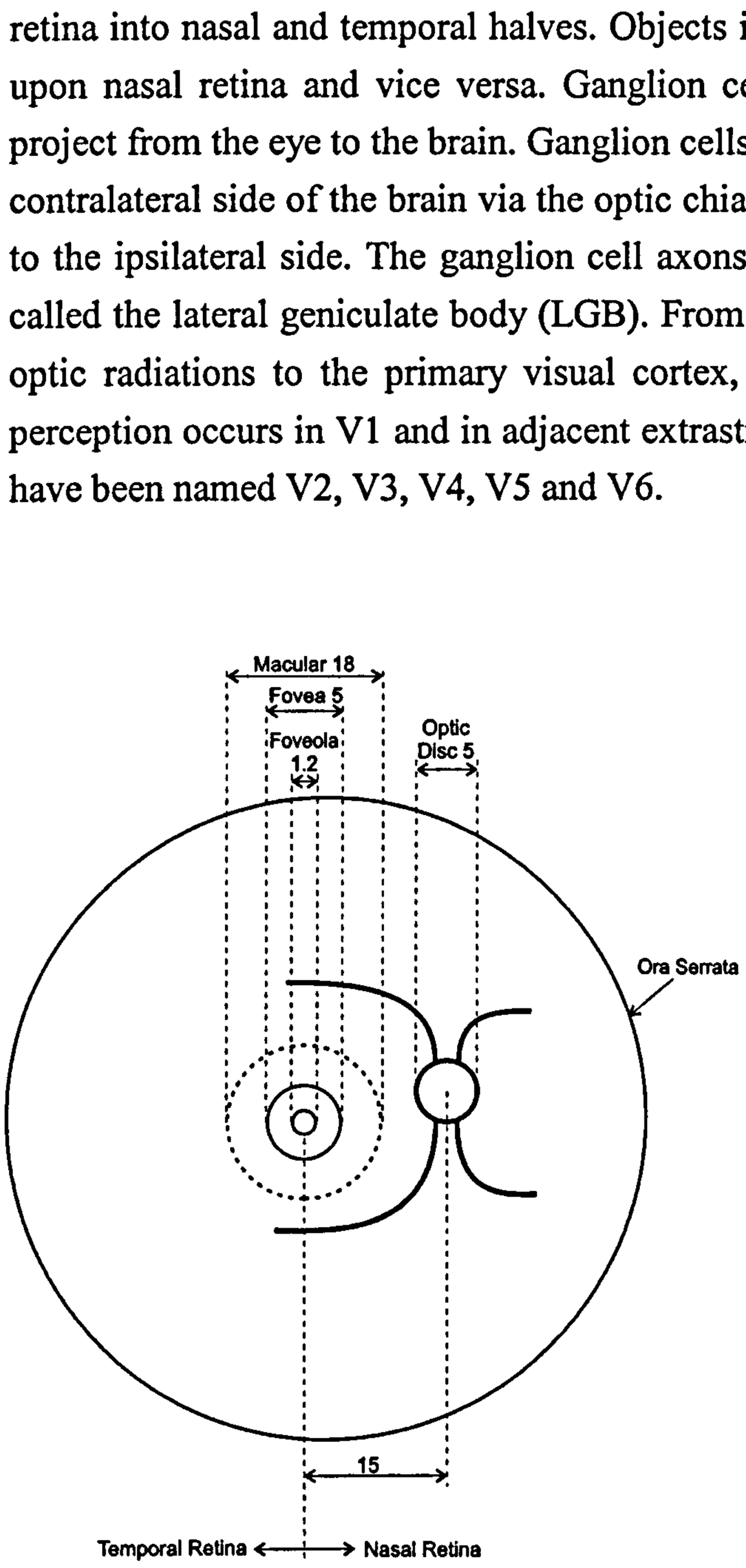

Figure 1.7: Retinal landmarks. Dimensions shown are in degrees and represent the approximate visual angle subtended by each structure.

1.2.1.2 Retino-collicular pathway (sub-cortical pathway)

Specialised retinal ganglion cells project axons, which exit the eye to the optic nerve and travel to the optic chiasm where nasal retinal fibres decussate and temporal fibres remain on the ipsilateral side. They follow the common visual pathway in the optic tract until they reach the thalamus. Here the fibres destined for the striate cortex pass into the lateral geniculate body, the retino-collicular fibres leave the optic tract and enter the brachium of the superior colliculus in the midbrain (see Figure 1.6).

1.2.2 Cortical areas involved in saccade generation

The areas involved in neurological sensory and motor processing of saccades are shown in Figure 1.8. The cortical areas will be described in this section, sub-cortical areas will be discussed in Section 1.2.3 and cerebellum will be described in Section 1.2.4.

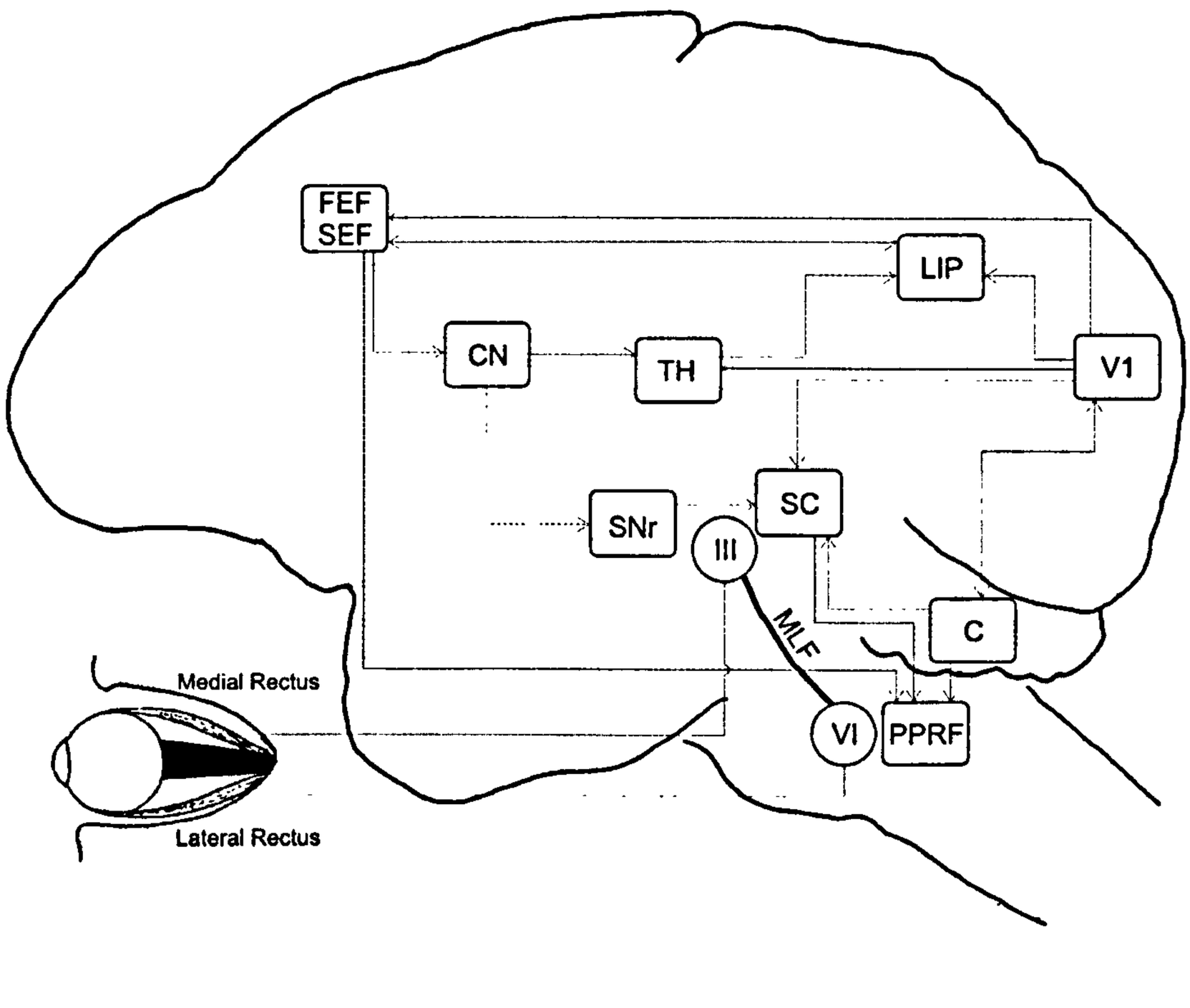

Figure 1.8: Schematic diagram of the major structures that participate in the control of horizontal saccades. Excitatory neurons are indicated by solid lines, inhibitory neurons by dashed lines. FEF, frontal eye fields; SEF, supplementary eye fields; LIP, lateral intraparietal area; V1, Striate cortex; CN, caudate nucleus; TH, thalamus; SNr, substantia nigra; SC, superior colliculus; C, cerebellum; PPRF, paramedian pontine reticular formation; MLF, medial longitudinal fasciculus; III, oculomotor nerve nucleus; VI, abducens nerve nucleus.

1.2.2.1 Striate cortex (V1)

Electrical stimulation of the striate cortex evokes saccades to the contralateral field. The amplitude and direction of the induced saccades resemble the sensory retinotopic map. Striate neurons project to the SC. Lesions of the SC result in the loss of saccades following electrical stimulation of the striate cortex (Schiller, 1977). This is thought to occur due to a lack of a direct pathway from the striate cortex to the oculomotor nuclei in the brainstem.

1.2.2.2 Extrastriate areas V2 and V5

Neurons of V2 discharge prior to saccades. It is unclear, however, whether this is purely related to the action of attending to a stimulus, rather than active processing related to saccade generation (Goldberg & Segraves, 1989).

Induced lesions of V5 (area MT, which receives input from V1 related to motion, velocity and direction) inhibit accurate saccades to moving stimuli in the field relating to the region affected by the lesion (Newsome, Wurtz, Dursteler & Mikami, 1985).

1.2.2.3 Frontal eye fields (Brodmann area 8)

The frontal eye fields (FEF), situated in the frontal lobes of the cortex, receive projections from extra striate areas V4, V5 (MT) and intraparietal sulcus. They also have input from the opposite FEF via callosal projections. A large projection from the FEF is to the intermediate and superficial layers of the SC. Other projections to the thalamus, basal ganglia, pretectum, rostral interstitial nucleus of the medial longitudinal fasciculus (riMLF) and the paramedian pontine reticular formation (PPRF) have also been identified (Feldon & Burde, 1992). The riMLF is the centre concerned with the generation of vertical eye movements, whilst the PPRF generates horizontal eye movements.

Electrical stimulation using electrodes penetrating the FEF have shown a complex topographic pattern with large amplitude saccades evoked by medial stimulation and small saccades by lateral stimulation. As the electrode progresses deeper into the cortex, the direction of the resulting saccade rotates. Areas of the FEF that produce large and small saccades project to areas of the SC that produce large and small saccades respectively (Komatsu & Suzuki, 1985).

Mohler, Goldberg and Wurtz (1973) have shown that almost half of the neurons in the FEF have receptive fields. They are generally large, up to a quadrant of the visual field, not selective for direction, speed, orientation, shape or colour. Hence they identify where the target is, but not what it is. Neurons that are active prior to saccades, active during and after saccades and neurons active during fixation have been identified in the FEF. Pre-saccadic neurons fire maximally prior to goal-directed saccades made to a target in their receptive field. Awareness of a target, which stimulates the receptive field, does not produce neuronal activity unless a saccade is made to the target (Goldberg & Bushnell, 1981). Post-saccadic neurons discharge in association with goal-directed and re-orientating saccades of all directions. Two types of neuron are involved in fixation. The first type discharge during fixation and the second type discharge when fixation is released (Suzuki & Azuma, 1977).

The characteristics of neurons that project from the FEF to the SC have been analysed by Goldberg and Segraves (1987). The two main groups of neurons were movement cells (majority pre-saccadic discharging neurons, very few post-saccadic neurons) and fixation cells. This suggests that the role of the FEF in generation of saccades is to specify the co-ordinates of the saccade (movement cells) and the maintenance and release of fixation (fixation cells) (Goldberg & Segraves, 1989).

1.2.2.4 Supplementary eye fields

Another area of the frontal cortex, which lies dorsomedially, has been found to produce saccadic eye movements when stimulated with electrodes and has therefore been named the supplementary eye field (SEF) (Schlag & Schlag-Rey, 1987). The cells of this area discharge prior to the saccade and project to the FEF, thalamus, SC and directly to the pons. Some cells in the SEF discharge maximally for saccades made at particular positions within the orbit. Also there is evidence that their response adapts with training. This has lead to speculation that this area acts as a pre-saccadic motor processing centre, which encodes spatial co-ordinates and motor behaviour based on training (Gaymard, Pierrot-Deseillingy & Rivaud, 1990).

1.2.2.5 Posterior parietal cortex

The posterior parietal cortex has been proposed to be crucial to generation of reflexive saccades (Gaymard, Ploner, Rivaud, Vermersch & Pierrot-Deseillingy, 1998). Lesions of this area in humans result in a deficit of involuntary saccades (Heide & Kompf, 1998). Microelectrode recordings in monkeys have established that neurons in the

parietal lobe give both sensory and motor related responses, suggesting a role in transformation of retinotopic visual signals into motor co-ordinates. The lateral intraparietal area (LIP) has been identified as a specific area related to amplitude and direction of intended saccades (Anderson & Gnadt, 1989).

1.2.2.6 Thalamus

The region of the thalamus involved in eye movements is called the internal medullary lamina (IML). Godlowski (1938) was first to recognise that electrical stimulation of this area resulted in contralateral saccades. It appears to be involved in the generation of saccades and co-ordination of head and eye movements and spatial representation of targets. As the IML has connections with the SC, FEF, posterior parietal lobe, basal ganglia, LGB, PPRF, vestibular nerve and cerebellum, it is hypothesised that it plays a role as a central controller (Schlag-Rey & Schlag, 1989). Schlag-Rey and Schlag, (1989) suggest that cells of the IML start and stop processing operations and regulate the transfer of information between centres. They also speculate that it may play a role in deciding which saccade commands should be prioritised, as several interpretations from the various centres will be received based on their individual inputs.

The pulvinar is the largest part of the thalamus, receiving inputs from striate cortex, extrastriate areas, parietal cortex, FEF and SC. It projects to striate cortex, extrastriate areas, parietal cortex and FEF. Two parts of the pulvinar have been identified having differing functions. The inferio-lateral aspect projects to V5 and discharges in relation to movement. This discharge reduces during saccades and has therefore been hypothesised to be involved in saccadic suppression[2] (Robinson, McClurkin, Kertzman, & Peterson, 1991). The dorsomedial region of the pulvinar is not retinotopically organised, it projects to the parietal lobe and appears to be involved with attention (Robinson, 1993).

1.2.2.7 Basal ganglia

The basal ganglia have a role in the generation of voluntary saccades and inhibition of inappropriate reflex saccades. The basal ganglia consist of the caudate nucleus and the substantia nigra pars reticular.

[2] Saccadic suppression is the ability to ignore visual input, which sweeps across the retina during saccadic eye movements. It prevents perception of fast moving blur as the eye moves.

- **Caudate nucleus:** This receives input from the FEF, SEF and IML of the thalamus. Its main projections are to the substantia nigra pars reticular (SNpr). The discharge of caudate neurons increases prior to saccades, particularly for memory guided saccades. It is thought that the caudate nucleus has a complex role in eye movement control, which involves predicting environmental changes (Hikosaka, Sakamoto & Usui, 1989).

- **Substantia nigra pars reticular (SNpr):** This receives input from the caudate nucleus and gives an inhibitory projection to the intermediate layers of the SC. Neurons within the SNpr have a high tonic discharge rate that decreases prior to saccades, particularly memory guided saccades. Stimulation of the caudate nucleus produces inhibition of the SNpr (Hikosaka, Sakamoto & Miyashita, 1993).

1.2.3 Sub-cortical areas involved in saccade generation

1.2.3.1 Superior colliculus (SC)

The SC is essential for the generation of a response to an object of visual or auditory interest. Descending pathways from the SC to the PPRF in the pons (an area of the brainstem involved in the generation of horizontal saccades) and reticulospinal cell groups, generate eye and head movements. The structure, inputs, outputs and function of the SC are outlined below.

The SC, which is sometimes referred to as the tectum, consists of seven layers, divided into dorsal (superficial) and ventral (deep) portions. Between these two portions are intermediate layers. The superficial portion is exclusively visual in terms of functions and connections. The deep portion has connections with multiple sensory and motor systems and appears to translate sensory signals into motor commands. One particular function is the initiation of rapid eye movements (saccades).

- **Superficial layers of the superior colliculus:** Input to the superficial layers of the SC occurs directly from retinal ganglion cell axons and projections from layer 5 of the striate cortex.

  The visual receptive fields of the superficial layers are organised in a retinotopic fashion (Cynader & Burman, 1972; Goldberg & Wurtz, 1972) as shown in Figure 1.9. The fovea is represented anteriorly with the horizontal meridian passing

posteriorly towards representation of the periphery. The upper visual fields are on the medial border and lower field on the lateral side. The central 10° of the visual field is represented by more than 30% of the SC (Cynader & Burman, 1972). In the macaque monkey, cells of the colliculus are not selective to the type, size or direction of the stimulus (Cynader & Burman, 1972). In the cebus monkey most cells have been found to be selective for size of stimuli and some are orientation specific (Updyke, 1974). Collicular receptive fields are larger than those of the geniculo-striate system and the field size increases with increasing depth within the colliculus (Goldberg & Wurtz, 1972).

- **Intermediate layers of the superior colliculus:** Neurons that discharge in relation to saccades are concentrated in the intermediate layers. Stimulation of these neurons of alert Rhesus monkeys evokes conjugate, contralateral saccades. The latency of the evoked saccades is about 20-30ms. A map of the amplitude and direction of saccades evoked by stimulation of different points of the SC was developed by Robinson (1972) (see Figure 1.9). Robinson noted that the correspondence between the motor map and the underlying sensory map were formed by the retinotopic projections to the superficial layers of the SC. Stimulation of caudal SC elicits large amplitude saccades and rostral stimulation evokes smaller saccades. Sparks and Mays (1983) found that the current required to evoke a saccade is greater if the animal is actively fixing a target and the amplitude of saccade is smaller. Also the direction and amplitude of saccades may be altered if stimulation occurs before a pending visually triggered saccade.

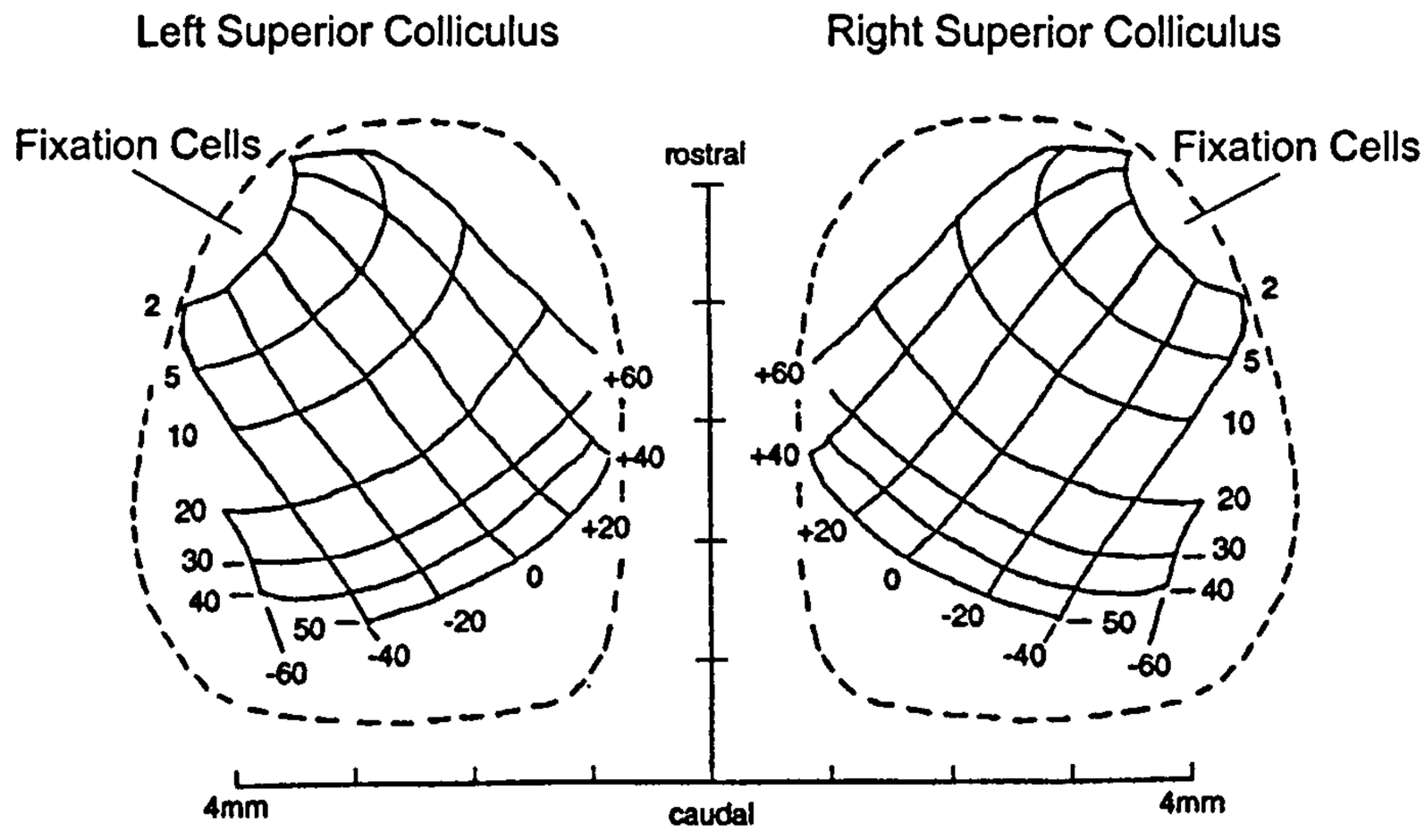

Figure 1.9 Schematic motor map of the intermediate layers of monkey superior colliculi. Isodirection lines run from the rostrolateral to caudomedial SC. Positive numbers represent upward directions and negative numbers downward directions. The rostral pole shows the fixation cells identified by Munoz and Wurtz, 1993a. Adapted from Robinson, 1972 by Munoz and Wurtz, 1993.

Cells in rostral SC of cats (Munoz & Guitton, 1991; Munoz, Guitton & Pelisson, 1991) and monkeys (Munoz & Wurtz, 1993a) have been shown to be maximally active during fixation. Munoz and Wurtz (1993b) demonstrated that stimulation of these 'fixation cells' has an inhibitory effect on saccades.

- **Deep layers of the superior colliculus:** Numerous ascending and descending afferent pathways enter the deep layers. In cats the deep layers receive extensive projections from the extrastriate visual areas. In monkeys, input from the posterior parietal cortex, an area important for visual attention, visuomotor discrimination and oculomotor control, has been demonstrated (Lynch, Graybiel & Lobeck, 1985).

Extensive inputs from the FEF have been documented in cats (Hartwich-Young & Weber, 1986) and macaque monkeys (Huerta, Krubitzer & Kaas, 1986). The FEF contains visually responsive neurons that discharge in association with saccadic eye movements. Communications between corresponding and non-corresponding regions of the two superior colliculi of cats have been found predominantly in the deep layers (Moschvakis, Karabelas & Highstein, 1986).

The large number of outputs from the deep layers of SC can be divided into two main categories; an ascending pathway to the thalamus, which may involve a complex feedback loop, and descending pathways, which convey collicular motor commands to nuclei within the brainstem and spinal cord. Ascending axons from deep SC have also been found to project to the riMLF, which plays a vital role in the generation of vertical saccadic eye movements (Buttner, Büttner-Ennever & Henn, 1977; Buttner-Ennever & Buttner, 1978). A large proportion of the descending fibres have been shown to be involved in oculomotor control, many projecting to the PPRF (Harting, 1977).

- **Physiology of the superior colliculus:** Two types of saccade-related neurons have been identified in the monkey SC (Munoz & Wurtz, 1995a and b). These are burst cells, which have a high frequency burst occurring just before saccades with no build-up of activity, and build-up cells, which show activity beginning with the signal to make the saccade that continues until the generation of the saccade. These cells are in two functional sub-layers within the intermediate layers of the SC. Fixation cells in the rostral SC, previously described by Munoz and Wurtz (1993a and b) were found to be part of the build-up cell layer. Munoz and Wurtz (1995b) proposed that during fixation, activity is confined to fixation cells in the rostral SC,

which suppress saccades via inhibitory connections to saccade cells in the caudal SC and excitatory connections with omnipause neurons in the PPRF (see below). Build-up cells show early activity prior to the saccade, related to preparation to make a saccade such as selection of target amplitude and direction. The burst cells are active just before the saccade and provide input to the pons for amplitude and direction of the saccade.

- **Lesion Studies:** Combined lesions of the FEF and SC give rise to a permanent impairment of saccades (Schiller, True & Conway, 1980). Removal of the SC does not prevent saccades evoked through stimulation to the FEF (Schiller, 1977; Shibutani, Sakata & Hyvarinen, 1984). Ablation of FEF has minimal effect of visually guided saccades, however impairment of saccades to command and predictive saccades to regular stimuli has been demonstrated in monkeys (Bruce & Borden, 1986). Saccades to remembered targets of contralateral field to the FEF lesion have also been shown in monkeys (Deng, Goldberg, Segraves, Ungerleider & Mishkin, 1986).

1.2.3.2 Paramedian pontine reticular formation (PPRF)

Bender and Shanzer (1964) and Bender (1980) defined two areas of the brainstem involved in conjugate gaze. One responsible for horizontal gaze in the pons known as the PPRF, the other involved in vertical gaze situated in the mesencephalon known as the riMLF. The PPRF is situated in the pontomedullary junction at the level of the VI nerve nucleus to the IV nerve nuclei[3], occupying 2 to 3mm on either side of the midline.

Fibres carrying activity for horizontal gaze pass from the SC, FEF and the cerebellum. They then decussate in the mesencephalon before passing to the PPRF. Inputs are also received from the vestibular nuclei and riMLF. Electrical stimulation of the PPRF evokes horizontal eye movements to the ipsilateral side, the size and velocity of movement being dependent on the stimulus frequency and duration. There are two main types of cell within the PPRF; burst neurons, which increase activity during saccades and omnipause neurons, which cease activity during saccades. Inhibitory and excitatory burst neurons have been identified within the PPRF to allow excitatory signals to be sent to agonist muscles and inhibitory signals to antagonist muscles. For example, to

[3] The VI nerve nuclei are the abducens nuclei from which the VI cranial nerves project to the ipsilateral orbits to supply the lateral rectus muscle. The IV nerve nuclei are the trochlear nuclei from which the IV cranial nerves leave the brain stem dorsally and decussate to pass to the contralateral orbit to supply the superior oblique muscle.

achieve a saccade to the right, excitatory signals would be required to the right lateral rectus and left medial rectus muscles whilst inhibition of the right medial rectus and left lateral rectus would be necessary to allow smooth rotation of the eye. Inhibitory burst neurons lie in an area of the PPRF called the nucleus paragigantocellularis dorsalis, are active prior to and during a saccade and project to the contralateral VI nerve nucleus. Excitatory burst neurons, which lie in an area of the PPRF called the dorsomedial nucleus reticularis pontis caudalis, receive inhibitory inputs from omnipause neurons and project to the ipsilateral IV nerve nucleus.

Büttner-Ennever and Horn (1999) found that different regions of the motor map of the SC give inputs to the excitatory burst neurons and omnipause cells as outlined in Figure 1.10. They suggest that this provides an anatomical basis for activation of burst cells and omnipause cells during saccade generation and for suppression of saccades from the rostral pole of the collicular motor map.

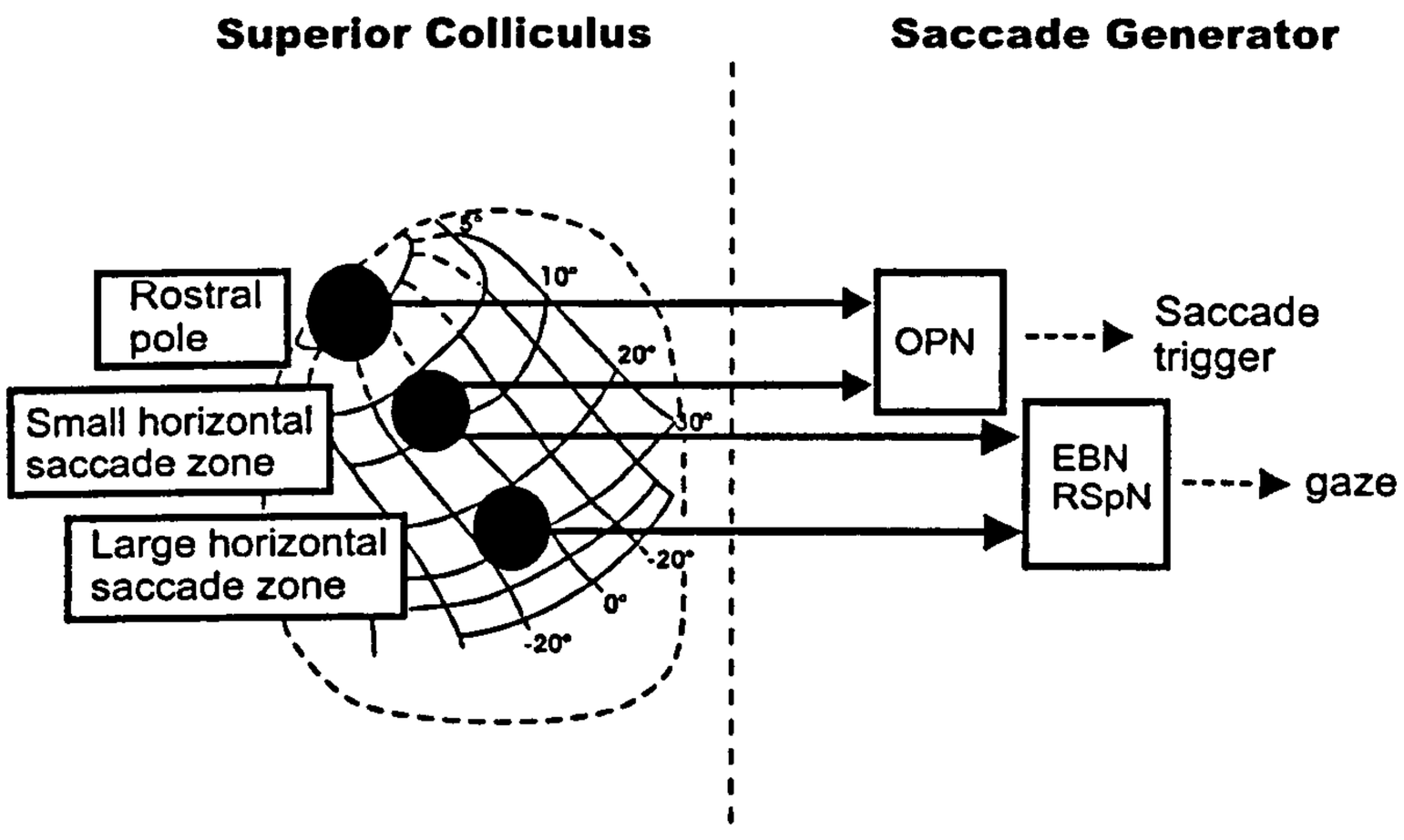

Figure 1.10: Connections between the SC and two cell groups of the horizontal saccade generator in the caudal pons: the omnipause neurons (OPN) and the excitatory burst neurons (EBN), which lie intermingled with reticulo-spinal neurons (RSpN). From Büttner-Ennever and Horn, 1999.

Horizontal eye movements are typically considered to be conjugate with both eyes being innervated by a common command signal yoking eye movements as stated in Herring's law of equal innervation (Herring, 1868). Zhou and King (1998) have provided evidence, which conflicts with this principle. Their results suggest that pre-motor neurons in the PPRF encode monocular commands for either right or left eye saccades. They suggest that organisation of the oculomotor system is probably monocular and may be related an evolutionary inheritance of lateral eyes that move independently. They also found existence of binocular motor neurons indicating that convergence of pre-motor monocular signals may be crucial for binocular co-ordination.

1.2.4 Cerebellum

The cerebellum has a central longitudinal structure called the vermis and two lateral hemispheres. Each hemisphere is connected to the vermis by an intermediate area called the paravermis. The hemispheres are divided into lobules; anterior, posterior and flocculonodular lobe. The vermis is also divided into ten lobules.

The cerebellum does not appear to be essential for the generation of eye movements as visually guided and memory guided saccades have normal latencies, velocities and amplitudes following cerebellar lesions. It does however seem to be involved in saccadic accuracy, as dysmetria is a common finding in humans with cerebellar lesions and animals with induced lesions. A secondary function appears to be gradual adaptation of saccades following dysmetria due to central or orbital lesions (Keller, 1989). Vermal lobules 6 and 7, and possibly 5 and 8, are the area of saccadic regulation. The flocculonodular lobe mediates inputs from the vestibular nucleus to the oculomotor system.

1.2.5 The neural integrator

As described in section 1.1.1 the pattern of innervation from brainstem to extraocular muscles consists of a pulse and step. The size of the pulse and step must be correctly matched to give an accurate eye movement that is maintained at the eccentric gaze position after it. The neural integrator integrates velocity-coded signals into position coded signals to achieve this. If the integrator does not function perfectly the eye position signal decays with time and the integrator is said to be leaky (Leigh & Zee, 1999). Clinically this would be evident, as following an appropriate saccade there would be a slow drift towards the midline, a corrective saccade would follow to reposition the eye to the required gaze eccentricity. A leaky neural integrator therefore results in the clinical picture of gaze evoked nystagmus.

In the presence of a leaky neural integrator restoring forces of the orbit pull the eye back towards the midline with a time course of a negative exponential (Leigh & Zee, 1999). The time constant of this exponential drift (i.e. 63% of drift back to midline) represents the level of function of the neural integrator, hence the longer the time constant the better the function.

The neural integrator depends on connections between a number of structures in brainstem and cerebellum. For horizontal conjugate eye movements the nucleus prepositus hypoglossi and the adjacent medial vestibular nucleus are most important. The nucleus prepositus hypoglossi is part of the perihypoglossal complex of nuclei situated medially to the vestibular nuclei and just caudal to abducens nucleus in the pons and has a strong projection to the abducens nucleus. The cerebellum, in particular the flocculus and paraflocculus, is also involved.

Lesions of nucleus prepositus hypoglossi result in partial failure of ipsilateral and contralateral gaze holding. Bilateral lesions abolish neural integration for all horizontal conjugate eye movements (Cheron & Godaux, 1987; Cannon & Robinson, 1987; Godaux, Mattens & Cheron, 1993).

Lesions of the flocculus and paraflocculus impair neural integration (Zee, Yamazaki, Butler & Gücer, 1981). The role of the cerebellum is thought to be to improve performance of an inherently leaky integrator in the brainstem.

1.3 Binocular vision

Slightly different images of the world are formed on the retina of each eye and are conveyed to the brain. If both eyes are used simultaneously binocular vision is said to be present. In the majority of people the two images are merged to give a single image, this is referred to as binocular single vision (BSV). BSV is usually achieved when the object of interest stimulates the fovea of each eye. This is referred to as bifoveal BSV, which occurs in the presence of normal retinal correspondence[4] (NRC).

Normal binocular vision is not only advantageous in giving an increased field of view, single vision and stereopsis, but also improves visual discrimination compared to monocular viewing and this is called binocular summation. Contrast sensitivity, visual acuity and flicker detection are all enhanced in binocular vision (Blake & Fox, 1973). Binocular summation is only apparent when the eyes are aligned. Jenkins, Pickwell and Add-Manan (1992) demonstrated that when fixation disparity was induced, using horizontal prisms in front of one eye, Snellen visual acuity reduced to the level found monocularly. In naturally occurring fixation disparity binocular visual acuity was found

[4] Normal retinal correspondence is a binocular condition in which the fovea and areas on the nasal and temporal side of one retina correspond to, and have a common visual direction with, the fovea, temporal and nasal areas of the retina of the other eye.

to increase when the disparity was prismatically corrected (Jenkins, Add-Manan, Pardhan & Murgatroyd, 1994).

1.4 Strabismus

This thesis includes experiments which tested the remote distractor effect and saccade adaptation in subjects with BSV (Chapters 5 and 7) and subjects with horizontal strabismus (Chapters 6 and 7). This section introduces the subject of strabismus followed by sections 1.4.1 and 1.4.2 which provide a brief summary of the aetiology and treatment of strabismus. Sections 1.4.3 to 1.4.5 then review the literature regarding sensory adaptations that may occur in strabismus, as this is the aspect most related to this thesis.

Strabismus is a common clinical condition in which the visual axes are misaligned such that only one eye, the fixing eye, looks directly at the target of interest. Heterophoria is a latent strabismus revealed only when the eyes are dissociated disrupting fusion. Heterotropia is a manifest strabismus present spontaneously without dissociation. The term strabismus is used to refer to heterotropia in this thesis. Heterotropia occurs in 2-5% of the population (Graham, 1974; Lennerstrand, 1987; Stayte, Reeves & Wortham, 1993) with approximately 65% of cases developing before the age of three years, and a mean age of onset of 30 months (Graham, 1974). The incidence of strabismus increases where there is a family history, with the risk being four times greater in the presence of strabismus in the family (Lennerstrand, 1987).

The direction of strabismus may be horizontal, vertical, torsional or a combination of these misalignments. Horizontal deviations can be divided into esotropia and exotropia, where one eye deviates nasally or temporally respectively. In unilateral strabismus one eye is used for fixation when both eyes are open and the other eye constantly deviates. Alternating strabismus occurs when the eye used for fixation swaps voluntarily or involuntarily. Strabismus may be associated with reduced vision (amblyopia), double vision (diplopia), loss of three-dimensional depth perception (stereopsis) and, in some cases, psychosocial difficulties (Burke, Leach & Davis, 1997; Coats, Paysse, Towler & Dipboye, 2000).

Strabismus may be concomitant, where the deviation is the same in all positions of gaze or incomitant where the angle of deviation varies with position of gaze. Incomitant strabismus may be caused by neurological, mechanical or myogenic conditions

affecting the oculomotor nerves or extraocular muscles. The aetiology of concomitant strabismus is less clear. It is concomitant strabismus with which this thesis is concerned. Concomitant strabismus, although typically equal in angle in all gaze directions, may change in size if the fixation distance is altered. This is often associated with accommodative effects where accommodative convergence increases eso deviations and reduces exo deviations for near fixation.

Strabismus may be described according to the age of onset of the deviation. Early onset or infantile strabismus, is typically a constant heterotropia, usually esotropic with onset within the first year of life (Costenbader, 1961; Lang, 1968). Evidence exists to suggest that strabismus does not occur until three to five months of age (Friedrich & De Decker, 1987; Archer, Sondhi & Helveston, 1989) which coincides with the onset of binocular vision, vergence and stereopsis (Aslin, 1977; Hainline, Riddell, Grose Fifer, & Abrahamov, 1992; Birch, Gwiazda & Held, 1983; Bradick, Wattam-Bell, Day & Atkinson, 1983). Late onset strabismus is generally considered to be that occurring after two years of age and may be constant or intermittent with potential for development of normal binocular single vision if corrected.

1.4.1 Aetiology of concomitant strabismus

1.4.1.1 Historical considerations

The aetiology of infantile strabismus remains unclear. The question remains whether the primary pathogenic factor is a sensory defect in the visual cortex that prevents motor fusion or a motor defect that prevents the development of sensory binocularity. Historically there were two main schools of thought. Worth (1901) proposed that strabismus was an inborn irreversible defect of the fusion faculty. It is not totally clear what the 'fusion faculty' means. It may be speculated that this implied a central cortical defect. Chavasse (1939) presented the 'nurture' theory that everything necessary for normal binocular vision was present at birth in strabismic individuals, but the development of fusion in the postnatal period was disrupted by abnormalities of sensory input to the eye or output to the extraocular muscles. Providing the obstacles to fusion could be removed at an early stage Chavasse believed that strabismus was curable.

Keiner (1956) postulated a defect of cortical binocularity compounded by direct sub-cortical 'light tonus' inputs. He found that the luminosity of objects in the visual field have an optomotor effect. Keiner claimed that neonates adduct if temporal retina is

stimulated and abduct if nasal retina is stimulated. When a balance between adduction and abduction is reached in each eye the result is orthophoria (i.e. no manifest or latent strabismus). Gobin (1968), based on work by Keiner, suggested that if one half of the retina is suppressed, a new balance between adduction and abduction is reached. This results in an eccentric part of the retina being directed towards the light, leading to a manifest squint, (esotropia if nasal retina is suppressed and exotropia if temporal retina is suppressed).

1.4.1.2 Birth trauma

Birth trauma may result in strabismus either when there is a direct trauma to an extraocular muscle or nerve or when there is resulting brain damage. Whether strabismus occurs as a symptom of cerebral palsy, anoxia, or as a direct result of the trauma, is difficult to determine.

McBride, Black, Brown, Dolby, Murray, and Thomas (1979) reported an increased incidence of strabismus in breech deliveries compared to normal vertex deliveries. Reduced stereopsis was also found post breech delivery. The theory is that pre-natal motor deficiencies exist which give rise to the abnormal vertex position and strabismus. McBride, Black, Brown, Dolby, Murray, and Thomas (1979) also compared normal vaginal delivery with caesarean section and found no significant difference in the incidence of strabismus.

1.4.1.3 Heredity

Manifest strabismus occurs in just 2-5% of the population and 60% of children with strabismus have a close relative with the same condition (Lennerstrand, 1987). Reduced horizontal vergence amplitudes and stereoacuity have been found in families of strabismic individuals (Niederecker, Mash & Spivey, 1972; Smith, Grutzner, Colenbrander, Hegmann & Spivey, 1972; Mash, Hegmann & Spivey, 1975; Cantolino & von Noorden, 1969). Defective motion processing has also been shown to be present in the parents of strabismics who do not themselves have strabismus (Tychsen, 1989).

There appears therefore to be a certain, but undefined, genetic component. It may be that the factors that predispose to strabismus are hereditary rather than the strabismus itself, for example refractive errors.

1.4.1.4 Refractive error

The presence of refractive error appears to be the main aetiological factor in certain types of strabismus, as correction of the refractive error eliminates the strabismus. For example, fully accommodative esotropia is corrected with the appropriate hypermetropic correction and in high hypermetropia accommodation becomes totally relaxed as there is no reward for accommodating, hence no accommodative convergence occurs and exotropia may develop. However, many people have equivalent refractive errors and do not produce strabismus, it is therefore likely that other factors are contributing.

Anisometropia, producing an habitually defocused image in one eye and subsequent foveal scotoma, has been considered the cause of microtropia[5] (Helveston & von Noorden, 1967).

Aurell and Norsell (1990) in a longitudinal study reported that hypermetropic children who developed strabismus showed less emmetropisation than non-strabismic hypermetropes.

1.4.1.5 Relationship of accommodation and convergence

For each unit of accommodation, an individual will produce a certain amount of convergence, known as accommodative convergence. This direct link between accommodation and accommodative convergence is the accommodative convergence to accommodation (AC/A) ratio. Using the gradient method[6] the AC/A ratio in normal subjects has been reported as 3:1 in adults (Plenty, 1988). Abnormally high or low amounts of accommodative convergence for each dioptre of accommodation may result in strabismus. This is typically seen in the case of convergence excess esotropia where a high AC/A ratio results in esotropia occurring only when exerting accommodation. Elimination of accommodation for near fixation with convex lenses results in correction of the esotropia.

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[5] Microtropia, first described by Lang, (1968b), is a small angled strabismus (≤10Δ) with a highly developed degree of binocular cooperation compared to other forms of heterotropia, however stereoacuity is reduced.

[6] The gradient method of measuring the AC/A ratio can be used with concave lenses at 6m or with convex lenses at 33cm. Measured at 6m the ratio is calculated using the equation:

(prism cover test with concave lenses - prism cover test without lenses) ÷ strength of lenses used

1.4.1.6 Maldevelopment of visual motion processing

Tychsen and Lisberger (1986) described deficits in visual motion processing in adult humans who had strabismus with onset in early infancy. The deficits were apparent in the pursuit eye movements evoked by moving targets and in the perception of motion. They proposed that a primary deficit in the cortical motion-processing pathway may lead to strabismus. This theory had the following basis; in the first months of life normal infants have an asymmetry in the optokinetic response that strongly favours nasally directed motion detection in each eye (Atkinson, 1979; Naegele & Held, 1982). This would provide a tonic drive that would promote crossed eyes. This nasally directed drive is opposed by a mechanism designed to keep the visual axes aligned, however a congenital maldevelopment of temporally directed motion processing could weaken the mechanism. The normal nasally directed bias would then dominate, driving both eyes nasally creating an esotropia.

If an infant develops normal binocular vision the nasally directed bias is replaced by a symmetrical response by three to five months of age. The pursuit and motion asymmetries found in early onset esotropia remain into adulthood providing a sign which enables later diagnosis of the early onset.

Removal of the visual cortex or monocular deprivation in cats gives rise to absence of temporally directed tracking whilst nasally directed tracking is unaffected (Hoffman, 1979). Hoffman hypothesised that this asymmetry occurred due to disruption to an ontogenetically and phylogenetically more recent cortical pathway which would normally produce temporal tracking. The nasal tracking would remain intact due to the sub-cortical pathway direct from the retina to the brainstem, which is not affected by deprivation.

There is partial agreement with this hypothesis in that temporally directed motion processing develops later and that it is more susceptible to deprivation than nasally directed motion detection pathways. However, the idea that cortical and sub-cortical pathways are involved in different directions of motion processing is disputed for three reasons (Tychsen, 1992). Firstly, visually evoked potentials[7] (VEP's) recorded over the occipital lobes of infants prior to three months of age show nasally directed bias in the responses, which would not be apparent if nasal responses were originating from the

[7] A visually evoked potential is a technique of examining the cortical response to visual stimuli using electrodes on the intact skull.

sub-cortical pathway. Secondly, humans with nasal bias in pursuit also have a nasal bias for velocity perception, which can only originate in the cortex. Finally, there are doubts over cats being used as a model for human pursuit deficits due to the lack of a developed fovea in the cat and the poorly developed feline pursuit system.

1.4.1.7 Evidence of cortical abnormalities

Changes within the cortex have been observed following induced strabismus in monkeys (Lund, Mitchell & Henry, 1978; Tychsen & Lisberger, 1986). A marked reduction in the binocularly driven striate cells is observed and a greater number of striate cells are monocularly driven by the contralateral eye (Crawford & von Noorden, 1979; Crawford, von Noorden & Meharg, 1983; Wiesel, 1982). These findings, however, do not significantly help in determining the primary site in the development of strabismus, as they may be the result of strabismus and not the cause. A study by Tychsen and Burkhalter (1995) report the findings in two naturally strabismic monkeys. Connections between ocular dominance columns revealed fewer lateral connections to the ocular dominance columns of the opposite eye. As an innate defect this could lead to strabismus by depriving vergence motor neurons of appropriate binocular error signals.

1.4.2 Treatment of strabismus

Subjects included in Chapter 6 and 7 had undergone various types of treatment for strabismus during childhood and in some cases during adulthood. The treatment for horizontal misalignment in childhood strabismus includes refractive correction, occlusion, orthoptic exercises, prisms and surgical correction. The latter is frequently required particularly for alignment of infantile esotropia. In the case of infantile strabismus it is accepted that restoration of normal BSV with bifoveal fixation is rare (Parks, 1984). The optimum result may be considered a residual small angle strabismus of <10 prism dioptres (Δ) potentially developing abnormal BSV. Success rates for correction of infantile esotropia appear high with many authors reporting 80-90% of cases being aligned to within 10Δ (Helveston, Ellis, Schott, Mitchelson, Weber, Taube & Miller, 1983; Kushner & Morton, 1984). The long-term results, however, are less impressive and this appears to be the case in both those who achieve motor success and those with initial motor and sensory success (Hiles, Watson & Biglan, 1980; Lunder, Mazow & Jenkins, 1985). The most common occurrence is for the gradual progression to consecutive exotropia in the post-operative months or years. Caputo, Guo, Wagner and Picciano (1990) highlighted the incidence of consecutive exotropia following

surgery for infantile esotropia; of those patients aligned to 10Δ at six weeks and remaining so at six months, exotropia occurred in 11% by three years and 25% at six years.

As the pathogenesis of strabismus has not been identified, treatment is directed at the manifestations. Unless the original defect can be identified and treated, the results of surgical alignment are, perhaps, more likely to be unstable over time.

1.4.3 Adaptations to strabismus

The aim of this thesis is to determine how binocular status impacts on the control of saccadic eye movements, in particular, to demonstrate whether sensory adaptations to strabismus affect generation of saccadic eye movements. The adaptations to strabismus, suppression and abnormal retinal correspondence, and mechanisms for these are discussed in this section.

The frontal placement of human eyes leads to an overlap of major parts of the right and left monocular visual fields. Most visible objects therefore stimulate both eyes simultaneously. In the presence of normal binocular vision, i.e. undisturbed visual orientation, retinal points that are stimulated by the same object in the plane of visual attention must be perceived in the same visual direction. So each retinal point of one eye has a partner in the other eye with identical localisation. For example, the foveae are corresponding retinal points and hence have the same visual direction. Objects that stimulate the fovea are perceived as being straight-ahead (principal visual direction). Likewise, a point on nasal retina of the right eye corresponds to a specific point of temporal retina of the left eye, and has the same visual direction. This retinal point-to-point relationship between the right and left eyes is known as normal retinal correspondence (NRC). Misalignment of an eye results in stimulation of non-corresponding retinal points, giving rise to diplopia, as shown in Figure 1.11. To avoid this disturbing symptom, adaptations may occur in strabismus, these being suppression or abnormal retinal correspondence (ARC).

1.4.4 Suppression

An important foundation of Experiments 5 and 7 is suppression. The vision of the strabismic eye may be suppressed to eliminate diplopia, particularly when the onset of

strabismus occurs in childhood. The consequence of suppression is a loss of binocular vision, loss of depth perception and essentially functioning as if 'monocular'.

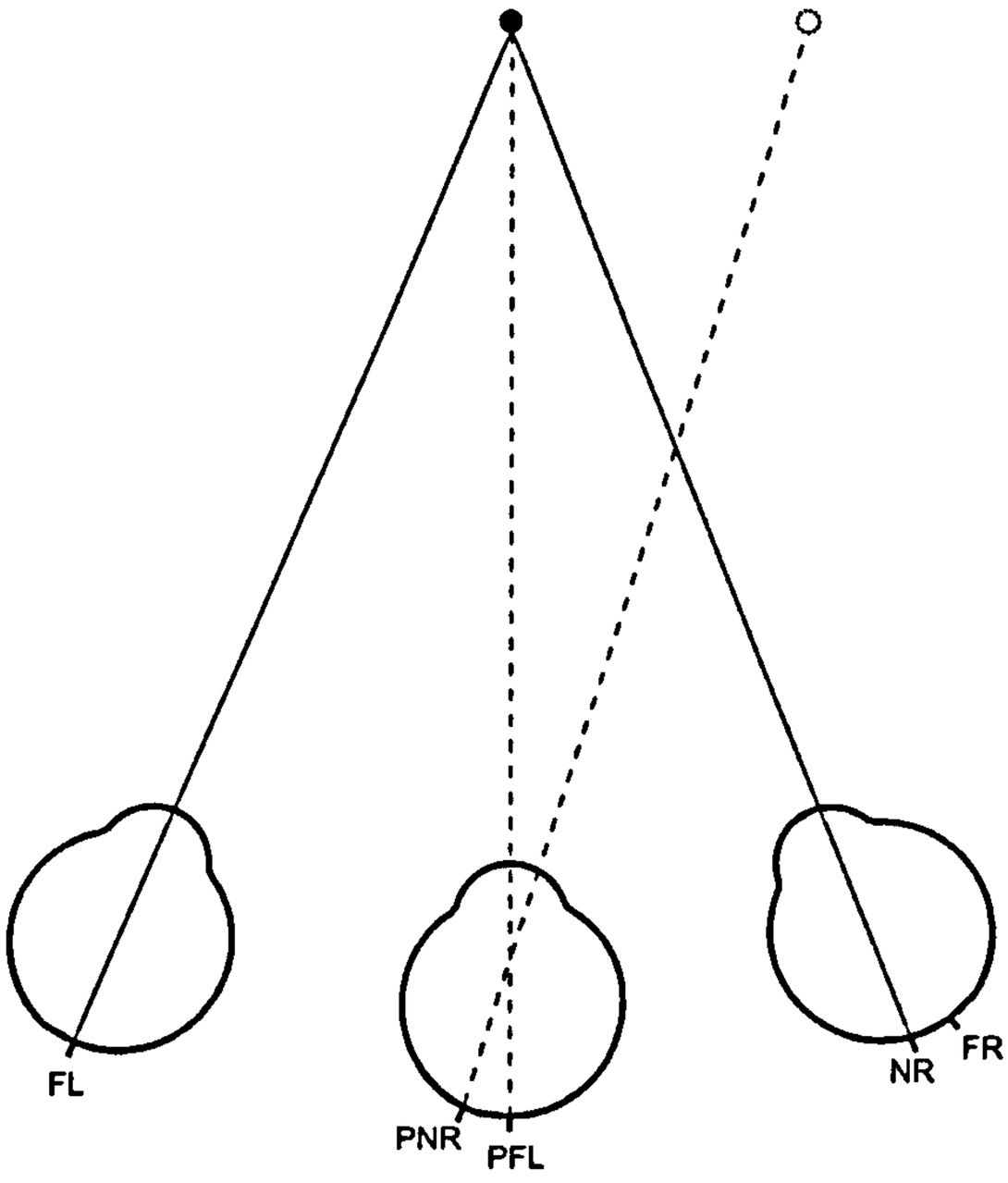


Figure 1.11: Right esotropia with NRC. The diagram represents a subject with a right esotropia. The left eye is fixing the target (represented by a red dot) with the fovea (FL), the target stimulates nasal retina (NR) of the right eye. The central eye (cyclopean eye) depicts the cerebral projection of retinal points and the subject's perception of the images in space. The fovea of the left eye (FL) projects straight ahead therefore the red dot is seen straight ahead. The nasal retina of the right eye projects temporally, hence a second image of the red dot is seen to the right hand side, this is known as pathological diplopia.

1.4.4.1 Area of suppression

Jampolsky (1955) investigated suppression areas using prisms and found nasal retinal suppression in esotropia and temporal retinal suppression in exotropia, termed hemiretinal suppression (Figure 1.12). As long as the image of fixation object fell on temporal retina in an exotropic eye and nasal retina in an esotropic eye, then suppression occurred. If the image was moved across the vertical foveal dividing line then diplopia was appreciated. This dividing border coincides with the line of separation between the crossed and uncrossed optical fibres.

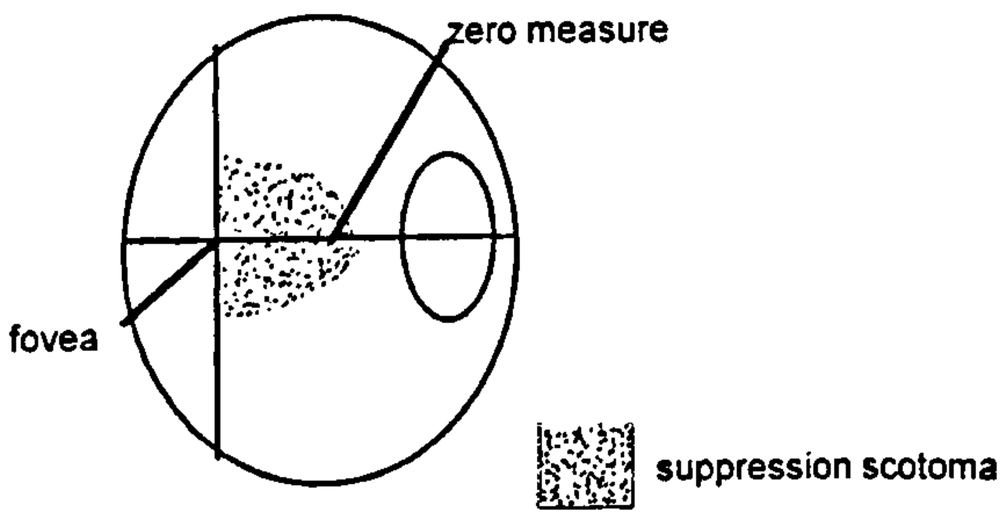


Figure 1.12: Hemiretinal suppression (Jampolsky, 1955)

Gobin (1968) confirmed the existence of hemiretinal suppression in esotropia and exotropia using the synoptophore. This theory, however, is not compatible with patients' symptoms, where diplopia of images falling outside the hemiretinal area does not occur.

Pratt-Johnson and Tillson (1983) disputed the concept of hemiretinal suppression and described suppression of the whole visual field. Using an Aimark perimeter they demonstrated that esotropes have a narrower field of vision and exotropes have a wider field of vision with both eyes open. Using an adapted Lees screen, suppression in all types of strabismus (except microtropia) was shown to involve the whole visual field of the deviating eye except the monocular temporal crescent (see Figure 1.13). No evidence was found to support Jampolsky's hemiretinal suppression theory, however subjects did appreciate diplopia if images were moved across the vertical foveal divide using prisms. Pratt-Johnson and Tillson (1983) described this as the hemiretinal trigger mechanism (Figure 1.14). When the image of fixation crosses the foveal divide, from nasal to temporal retina or vice versa, this operates the trigger mechanism determining whether diplopia or suppression occurs. In the presence of strabismus the image of the fixation object falls on the same side of the retina and is suppressed. If the deviation changes, or the image is moved on the retina with prisms so that it crosses from one half of the retina to the other, diplopia is triggered wherever the visual fields overlap. This theory is consistent with clinical experience.

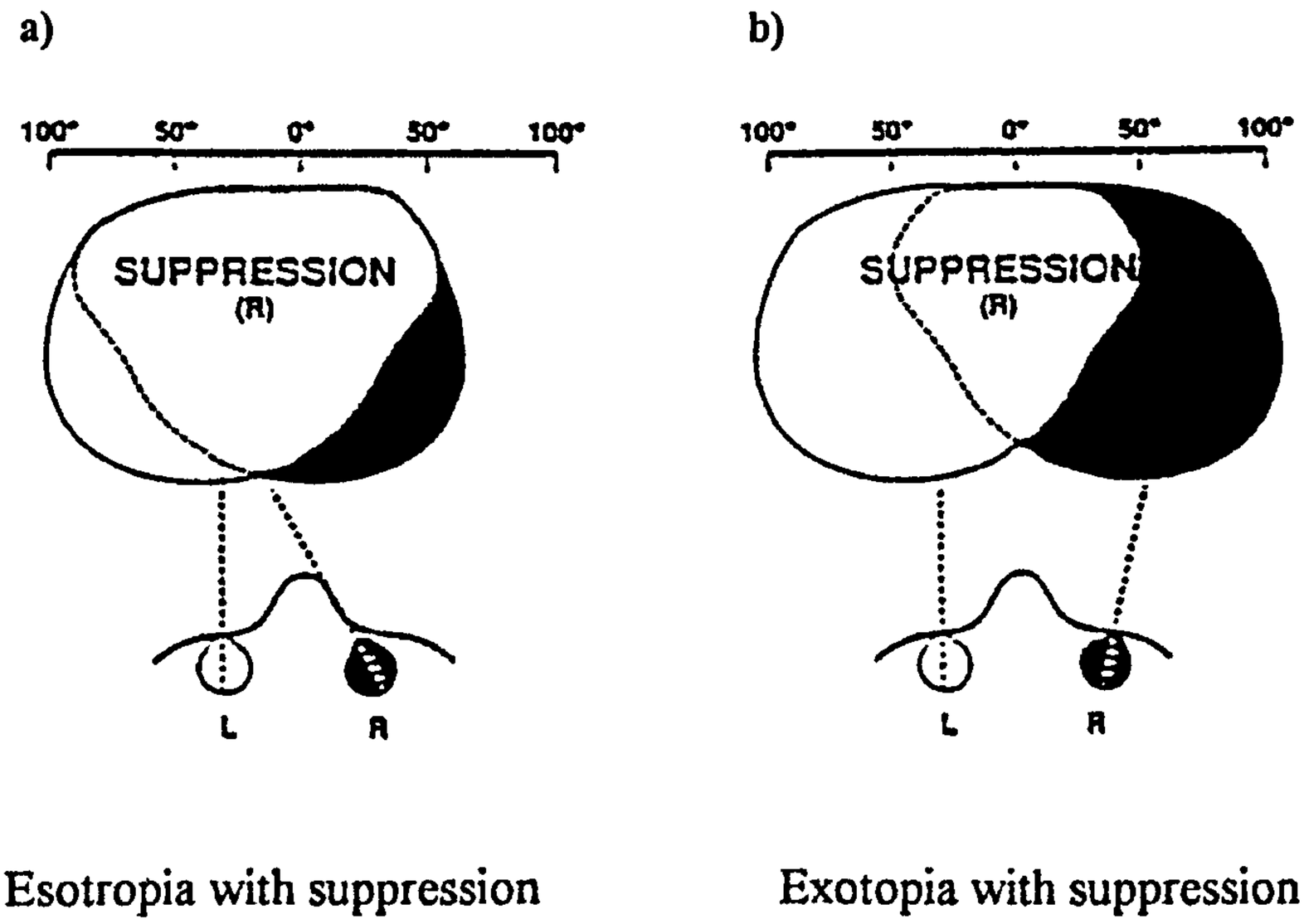


Figure 1.13: Suppression of the whole visual field of the strabismic eye, except the monocular temporal crescent represented by shaded area; a) right esotropia, b) right exotropia (Pratt-Johnson & Tillson, 1983).

Differences in the size and shape of suppression areas between studies may be a result of the type of testing method and size of the target used. Jampolsky (1955) stressed the need for tests determining suppression to be as representative of everyday viewing as possible.

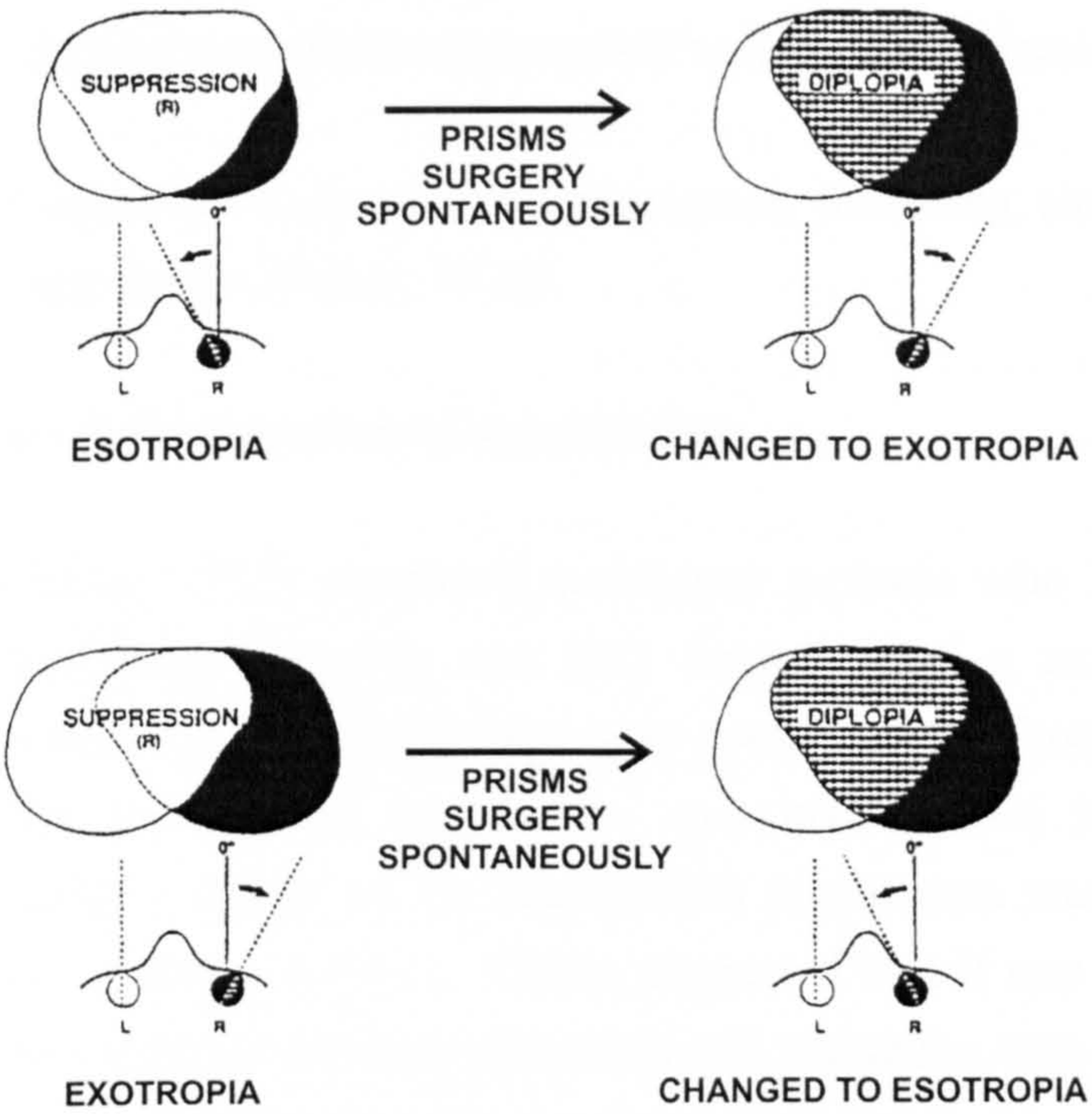


Figure 1.14: Hemiretinal trigger mechanism. In the presence of constant esotropia (top diagrams) there is suppression of the whole visual field of the strabismic eye, except the monocular temporal crescent. This is triggered by stimulation of nasal retina by the object of fixation. If the strabismus is over corrected so that the object of fixation stimulates temporal retina, diplopia is triggered. The bottom diagrams represent this mechanism in exotropia (Pratt-Johnson & Tillson, 1983)

The difficulty found when studying suppression in strabismus, as acknowledged by Harrad (1996), is that in order to distinguish between the stimuli presented to the two eyes they need to be different in some way. Schor (1977) and Jampolsky (1995) have shown that similar stimuli are more likely to produce suppression than dissimilar stimuli, therefore the nature of stimuli during investigation of suppression can lead to the elimination of suppression under such testing conditions.

1.4.4.2 Density of suppression

Using red filters to measure the density of suppression at different points on the retina, Jampolsky (1955) found that the zero measure point, i.e. the retinal point equal to the angle of deviation, was the area of densest suppression. Holopigian, Blake and Greenwald (1986) measured the depth of suppression in amblyopes and found an inverse correlation between the depth of suppression and the depth of amblyopia. Alternating strabismics demonstrated the densest suppression, constant unilateral strabismics showed fairly dense suppression and anisometropic amblyopes the weakest.

Blake (1989) also found that alternating strabismus demonstrated the most powerful suppression and suggested that it occurs as it is necessary to overcome or inhibit the large monocular pool of cells, within the striate cortex, driven by the contralateral eye. Harrad and Hess (1992a) demonstrated weak orientationally tuned suppression in anisometropic amblyopes with microtropia and central suppression and more powerful (denser) suppression in constant unilateral strabismics.

Central nervous system depressants, including alcohol, have been shown to weaken suppression (Fukai, 1972).

1.4.5 Mechanisms of suppression

Gobin (1968) examined amblyopic patients who had never demonstrated a manifest strabismus. Finding that they demonstrated a small central area of suppression he concluded that suppression may occur before a horizontal deviation. He also suggested that hemiretinal suppression was instrumental in the development of strabismus. Gobin's theory of the suppression mechanism was based on work by Keiner (1956), (see Section 1.4.1.1). Gobin suggested that if one half of the retina was suppressed, a new balance between adduction and adduction was reached with an eccentric part of the retina directed towards the light. This resulted in a manifest squint, esotropia if nasal retina was suppressed and exotropia if temporal retina was suppressed.

1.4.5.1 Retinal rivalry suppression

When subjects with normal binocular vision view different stimuli with each eye, they see an unstable percept, which fluctuates from one monocular stimulus to the other, and rarely both stimuli are seen at the same time. This competition for perceptual dominance is called binocular or retinal rivalry. It has often been postulated that the suppression seen in binocular rivalry has the same mechanism as pathological suppression seen in strabismus (Fahle, 1983; Wolfe, 1983; Sengspiel, Blakemore & Harrad, 1995). Wolfe (1983) has shown that normal retinal rivalry suppression does not occur when stimuli are briefly presented for less than 150ms. This finding was replicated in a later study of strabismic suppression, which found a similar cut-off point of 150ms (Wolfe, 1986). Stimuli presented for durations of less than 150ms resulted in simultaneous perception, whereas stimuli presented for more than 150ms resulted in pathological constant suppression. Conclusions were drawn from the similarities in these two studies, that both physiological suppression and pathological suppression require 150ms of

stimulation to be made manifest. Wolfe suggests therefore that the mechanisms for retinal rivalry suppression and pathological strabismic suppression are similar.

Clinical observations and research studies throw doubt on this theory. The characteristic alternation of rivalry is not generally seen and strabismic suppression is generally much more stable in nature. The strength of suppression in strabismus has been found to be much stronger than rivalry suppression in normals (Crawford, Smith, Harwerth & von Noorden, 1984). Binocular rivalry suppression shows wavelength dependent characteristics that differ from those found in strabismic suppression. Rivalry suppression in normal subjects involves selective reduction in the sensitivity of chromatic mechanisms relative to luminance mechanisms, such that in a rivalrous suppressing phase they show reduced sensitivity to wavelengths between 400-460nm. This is in contrast to the suppressing eye in strabismus, which shows reduced sensitivity that is independent of stimulus wavelength (Smith, Levi, Manny, Harwerth & White, 1985). Visual stimuli, such as gratings at different orientations, that lead to binocular rivalry tend to stimulate a classic rivalry response rather than suppression in strabismics, (Schor, 1977). It is a possibility that strabismic suppression is a modified form of binocular rivalry.

1.4.5.2 Dichoptic masking

In individuals with normal BSV, if a stimulus of a particular contrast is presented to one eye it prevents detection of an identical stimulus of lower contrast in the other eye. This is known as dichoptic masking (Abadi, 1976). Harrad and Hess (1992b) suggested that this mechanism could be operating in strabismus to create suppression in the presence of amblyopia. They postulated that as amblyopic subjects have reduced contrast sensitivity in the amblyopic eye compared to the normal eye, the normal eye would always receive higher contrast images. By dichoptic masking this would reduce perception of the image in the strabismic eye leading to suppression.

Although this theory is satisfactory to explain suppression in the presence of amblyopia it may not explain the often dense suppression found in strabismus in the absence of amblyopia. It could, however, suggest that different mechanisms operate depending on the type of strabismus and level of amblyopia.

1.4.5.3 Disparity specific or fusional suppression

Fusional suppression occurs in the presence of normal binocular stereopsis. When viewing a stereoscopic image the half image seen by each eye may contain areas that are not perceived in the stereoscopic image. This suppression in the presence of fusion has been described as a possible mechanism in small angle strabismus in the absence of amblyopia (McKee & Harrad, 1993).

1.4.5.4 Saccadic suppression and physiological suppression

Saccadic suppression eliminates vision during saccades to avoid a blurred image or the appearance of motion as the visual field sweeps across the retina. A proposed mechanism for this type of suppression is that raised sensitivity before and after a saccade masks out the motion on the retina during the saccade (Campbell & Wurtz, 1978; Moore, Tolias & Schiller, 1998). The site of saccadic suppression is unknown however it has been suggested that it selectively involves the magnocellular pathway, as this involves information from peripheral retina and detection of motion, and may occur in the lateral geniculate body (Ross, Burr & Morrone, 1996). It obviously has a quite different purpose and mechanism to suppression occurring in strabismus.

Physiological suppression occurs in normal BSV to eliminate physiological diplopia. This type of diplopia occurs as objects located in front of and behind the object of fixation stimulate non-corresponding points. Physiological suppression is therefore a constant requirement of normal BSV. Von Noorden and Campos (2002) suggest that we become conditioned to binocular seeing and hence to physiological diplopia. They propose that physiological suppression occurs at a psychological level, which depends on the attention value of the image to be ignored, whereas, pathological suppression in strabismus is an active inhibition of afferent visual information involving a neurophysiologic process.

1.4.6 Site of suppression

Suppression is often described with reference to the retina, but the actual site and mechanism of suppression has been the subject of debate. With the greater use of neurophysiological techniques increasing evidence for cortical involvement in the suppression mechanism has been established.

1.4.6.1 Evidence for retinal or pre-cortical involvement

Differences in pupillary responses in the fixing and suppressing eye in subjects with binocular vision, under conditions of retinal rivalry, or in strabismus may suggest that the site of suppression is not cortical. The pupillomotor pathways in the light reflex leave the optic tract before the LGB and pass to the midbrain. Hence, a common pathway for pupil responses and suppression suggests the absence of cortical control.

Bárány and Halldén (1948) noted that pupillary constriction was less marked in suppressed eyes during retinal rivalry than in normals. This was not confirmed by Lowe and Ogle (1966) when they repeated the experiments of Bárány and Halldén, using a more accurate objective measurement of the pupillary responses. However, in strabismic subjects Brenner, Charles and Flynn (1969) found reduced pupillary responses to light in the suppressing eye compared with the fixing eye. The pupil response became weaker with deeper suppression and amblyopia.

1.4.6.2 Evidence for cortical involvement

Van Balen (1964) studied retinal rivalry with simultaneously recorded electroretinogram (ERG)[8] and VEP and found no reduction in the ERG even when the VEP was reduced, thus suggesting a post-retinal site for the suppression mechanism in normal retinal rivalry.

Franceschetti and Burian (1971) studied VEP of patients with alternating esotropia and found responses of larger amplitude when the fixing eye was stimulated compared to when the deviating eye was stimulated. The effect on VEP amplitudes reversed when fixation was swapped, always giving larger amplitudes when the fixing eye was stimulated. This suggested that cortical cells participate in the suppression mechanism.

Wright, Ary, Shors and Eriksen (1986) studied transient VEP and found reduced responses when retina within an area of suppression was stimulated compared to non-suppressing areas, providing evidence for a cortical origin to suppression.

Hess (1991) utilised spatial adaptation to investigate the mechanism of suppression. Adaptation occurs in a normal subject whereby, if a high contrast grating of a certain

[8] An electroretinogram is the recording of alterations in electrical potential of the retina in response to a light stimulus.

spatial frequency is viewed, sensitivity for detection of the same or similar pattern is subsequently reduced (Blakemore & Campbell, 1969). Adaptation is spatial frequency dependent, orientationally selective and exhibits the property of interocular transfer. Interocular transfer occurs when one eye is exposed to a particular spatial frequency grating which has the effect of reducing the sensitivity of the other eye to a grating of similar spatial frequency. The reduction in sensitivity is greater in the stimulated eye than the interocular transfer sensitivity loss. The site of spatial adaptation is known, from animal experiments, to be within the striate cortex (Maffei, Fiorentini & Bisti, 1973; Movshon & Lennie, 1979; Sclar, Lennie & DePriest, 1989). Hess proposed therefore that if adaptation could be shown to occur in the strabismic (suppressing) eye when both eyes were open then suppression must take place at a site beyond the site of adaptation (striate cortex). On the other hand if adaptation did not occur in the suppressing eye following stimulation with both eyes open, then the site of suppression must be at the same anatomical area as adaptation, or earlier in the visual pathway. Hess (1991) found that no adaptation occurred from the suppressing eye indicating that the site of suppression is not beyond the site of adaptation, but at the same or an earlier site.

In a second experiment Hess (1991) looked for sensitivity to targets of different orientation presented to the two eyes at the same time. The sensitivity of the suppressing eye was orientation specific. As areas of the visual pathway prior to the striate cortex are not orientationally sensitive this places the site of suppression within the striate cortex close to the site of adaptation.

Crawford, Smith, Harwerth and von Noorden (1984) found sharply defined ocular dominance columns for right and left eyes in strabismic monkeys with a loss of binocular neurons. Excitatory intrinsic connections between neighbouring ocular dominance columns are selectively lost leaving only inhibitory projections in the majority of cells. There is also indirect (psychophysical) evidence that this is also true in humans (Blake & Cormack, 1979).

Horton, Hocking and Adams (1999) surgically induced exotropia in six normal adult macaque monkeys by disinserting their medial recti. Four to eight weeks later the exotropia was measured and fixation preference was determined. The ocular dominance columns were examined to assess local metabolic activity and two distinct patterns were found. In those monkeys with a fixation preference for one eye thin dark columns alternated with wide pale columns. This pattern arose from reduced metabolic activity in the monocular core zones in the suppressed eye and binocular zones of both eyes. In

monkeys with alternating fixation thin pale bands were found from reduced metabolic activity in binocular areas of both eyes. The authors concluded that this was the first anatomical evidence for changes in cortical metabolism that could be correlated with suppression scotomas in strabismus. It is not stated however, whether suppression was actually demonstrated in these animals. Clinical findings in humans would suggest that it is unlikely that suppression would develop in strabismus induced in adulthood as such patients tend to be constantly aware of diplopia.

From the majority of evidence it appears that suppression in strabismus results from a cortical loss of perception, but whether the eye continues to give a sub-cortical input is unknown.

1.4.7 Abnormal retinal correspondence

An alternative adaptation in strabismus is abnormal retinal correspondence (ARC) which was present in the subjects of Experiment 8, Chapter 6. ARC is a binocular condition in which there is a change in visual projection such that the fovea of the fixing eye (non-strabismic eye) has a common visual direction with an area other than the fovea of the strabismic eye (pseudo-fovea). The pairing of all retinal elements is similarly changed. The resulting abnormal binocular vision is of lower quality to that achieved in normal binocular viewing without strabismus, however it typically gives rise to depth perception and eliminates diplopia.

ARC can be divided into two types; harmonious and unharmonious. Harmonious ARC occurs when the retinal point of the deviating eye, equal to the angle of deviation, corresponds to the fovea of the fixing eye (see Figure 1.15). Hence, the difference between the objective and subjective angle[9] of deviation (angle of anomaly) is equal to the objective angle of deviation. The subjective angle in this case will be zero. In unharmonious ARC a point other than that equal to the angle of deviation corresponds to the fovea of the fixing eye. Hence the angle of anomaly is less than the objective angle of deviation as the subjective angle of deviation is greater than zero.

[9] The objective angle is the angle of misalignment of the visual axes as measured by the examiner. The subjective angle is the subject's perception of misalignment of the visual axes.

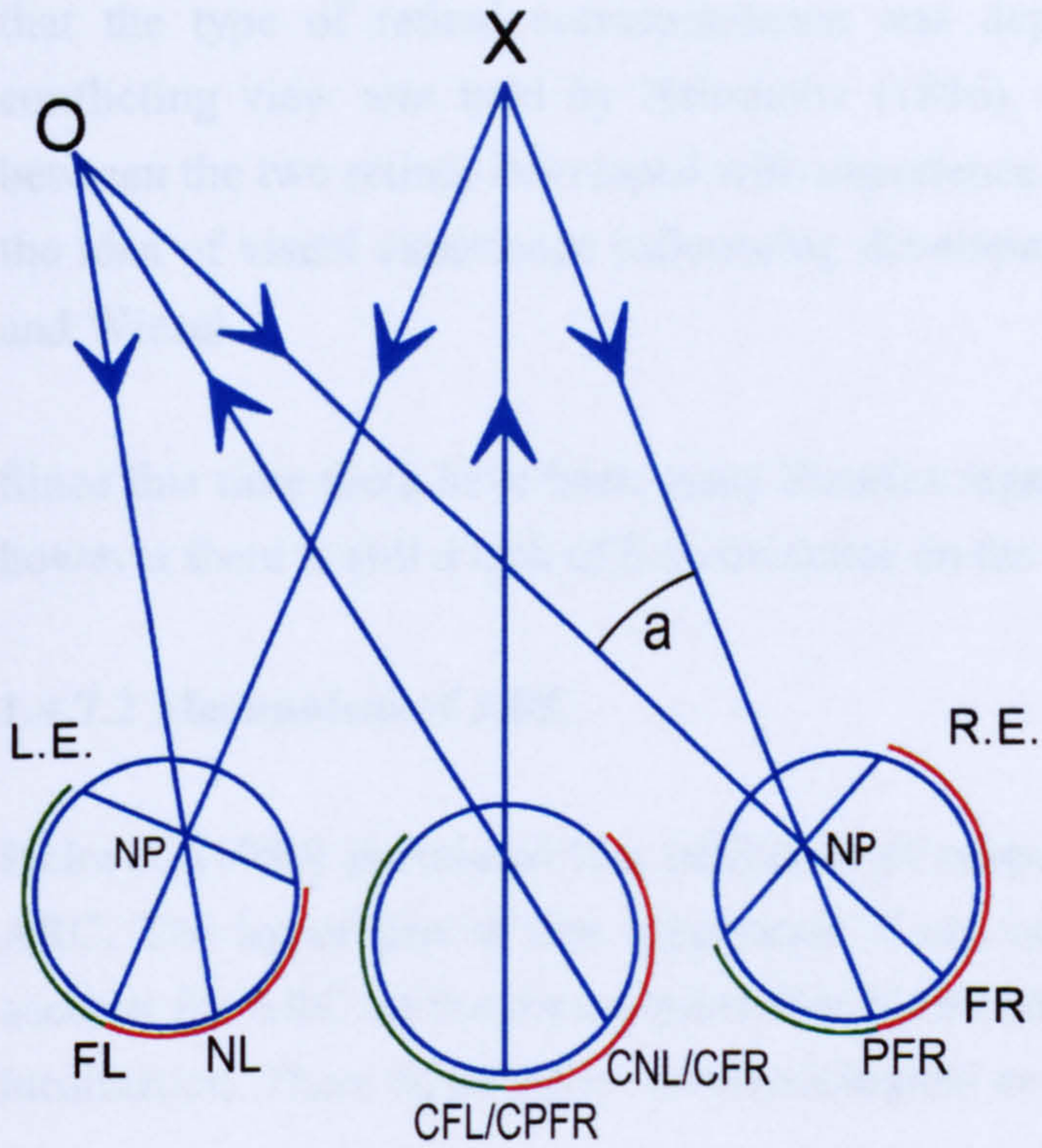


Figure 1.15: Projection diagram representing harmonious ARC in right esotropia. The fovea of the left eye (FL) corresponds to the pseudo-fovea of the right eye (PFR). The pseudo-fovea is equal to the point representing the angle of deviation, therefore the fixation point X stimulates the left fovea and right pseudo-fovea. Both project straight ahead hence the object X is seen singly. The objective angle of deviation (angle a) is the angle between the fovea and pseudo-fovea of the right eye. The subjective angle is zero, as point PFR equals the angle of deviation. The central eye (cyclopean eye) depicts the cerebral projection of the images in space. CFL = cerebral projection of left fovea, CFR = cerebral projection of right fovea, CPRF = cerebral projection of right pseudo-fovea, CNL = cerebral projection of the left nasal retinal point NL.

Moncrieff (1929) and Burian (1958) both considered unharmonious ARC to occur due to an increase in size of deviation, changing ARC from harmonious to unharmonious. Travers (1938) proposed that unharmonious ARC preceded harmonious ARC as a stage in its development. Cass (1938) considered harmonious ARC to be the primary condition with unharmonious ARC being a stage in the treatment of ARC towards achieving NRC. Unharmonious ARC has also been explained as an artefact of testing techniques (Hallden, 1952; Levinge, 1954). This view was further consolidated by Fitton (1967) and Romano, von Noorden and Awaya (1970), who demonstrated that the type of ARC is dependent on the method of assessment used.

1.4.7.1 Historical theories on development of ARC

ARC was first described as 'strabismus incongruous' by Müller in 1826. Von Graefe (1855) first described paradoxical diplopia occurring as a consequence of surgical intervention in cases of ARC. Early thinking by Müller and von Graefe suggested that the anomaly was due to a misplaced macula. Cover test responses and the use of the ophthalmoscope have clearly ruled out this possibility.

The theory of ARC being a sensory anomaly present at birth was proposed by Herring (1861). This was later supported by Verhoeff (1938) and Adler (1947) who proposed

that the type of retinal correspondence was dependant upon hereditary factors. A conflicting view was held by Helmholtz (1856), who suggested that the relationship between the two retinae developed with experience. The most direct evidence to support the idea of visual experience influencing development was provided in 1962 by Hubel and Wiesel.

Since this time there have been many theories regarding its aetiology and development, however there is still a lack of firm evidence on the subject.

1.4.7.2 Mechanism of ARC

Pickwell (1980) postulated that inhibition of subpopulations of cells could account for ARC. The hypothesis is that suppressed Y-cell activity from the deviating eye could account for ARC on the presumption that Y-cell activity is important for normal spatial localisation. There is, however, no physiological evidence to support this theory.

Boeder (1964) considered binocular responses in the presence of strabismus to occur in the presence of NRC. His 'response shift' mechanism involved a shift in spatial localisation such that, in esotropia, when the nasal retinal point equal to the angle of deviation is stimulated it responds to the visual direction of the fovea.

Dengler and Kommerell (1993) quantified the largest amount of visual disparity that could still produce depth information in normal human subjects. Stimuli were projected onto the fovea of one eye and either nasal or temporal periphery of the other eye. For crossed disparities in six subjects the range of thresholds for appreciation of stereopsis was 6 to 21°. Uncrossed disparities from 3 to 9° allowed stereopsis. This was, however, the maximum uncrossed disparity tested due to the blind spot. They proposed that this demonstrates that anomalous binocular vision in strabismic patients includes the fovea of the deviating eye and not the peripheral retinal point equal to the angle of deviation.

Nelson (1981) has also demonstrated plasticity of correspondence in normal BSV and proposed that an extension of this occurs in ARC such that an intracortical shift of disparity detector activity occurs from the foveae to a convergent disparity in exotropes or divergent disparity in esotropes.

1.4.7.3 Neurophysiological and anatomical evidence for the mechanism of ARC

As the primary visual cortex (area VI) has been shown to be the first point in the visual pathway containing binocular neurons (Hubel & Wiesel, 1968), it would seem the most likely site for neural connections to give rise to anomalous binocular vision in ARC.

The early components of pattern VEPs in humans probably arise from striate and parastriate cortical activity (Jeffreys & Axford, 1972a and b). Topography of the VEP response is a technique to examine the spatial distribution of the VEP amplitude over the posterior scalp. They reported VEP topography to be correlated to retinotopic mapping in the visual cortex. If ARC occurs due to the retinotopic mapping of the deviating eye undergoing a physiological shift in the striate cortex during binocular viewing then this should be demonstrable using VEP topography. Early VEP studies confirmed normal retinotopic mapping during monocular vision in strabismus with ARC (McCormack, 1975).

McCormack (1990) searched for retinotopic remapping in five esotropes and one exotrope with ARC. Uniocular stimulation of both foveae (corresponding points) during binocular vision in a non-strabismic binocular subject produced identical VEP scalp topographies from each eye. In the six strabismic subjects stimulation of anomalously corresponding points (fovea/psuedo-fovea) produced different VEP scalp topographies. Stimulation of both anatomic foveae during binocular vision in these subjects produced identical VEP scalp topographies. The absence of a retinotopic shift in this study suggests that no topographic shift occurs at any cortical site contributing to the pattern-onset VEPs (areas 17 and 18). McCormack does acknowledge, however, that it could be possible that sub-populations of visual cortex cells undergo retinotopic re-mapping due to ARC, but these are not revealed by VEPs because they are electrophysiologically silent or that there are too few to make a difference to the VEP.

The results of McCormack (1990) are not in agreement with the earlier work of Campos (1980) and Campos and Chiesi (1983) which considered binocular summation effects of VEPs to identify the presence of ARC. Their findings of a larger binocular VEP than monocular VEP response was taken as evidence for binocular vision in strabismus with ARC. The technique used in these studies was considerably different, as the stimuli used by Campos (1980) and Campos and Chiesi (1983) were large and not specifically directed at anomalously corresponding points as in the work of McCormack (1990). Hence, the increased binocular response recorded may be produced from different

retinal regions in the two eyes, which activate physiologically separate cortical points whose electrical responses sum at the recording electrode.

Wong, Lueder, Burkhalter and Tychsen (2000) studied five macaque monkeys (three strabismic and two non-strabismic) and a group of 192 children with strabismus to determine the neural architecture in ARC. They hypothesised that if the neural connections required for ARC occur in the striate cortex, horizontal neurons connecting right-eye and left-eye ocular dominance columns (ODC) would be present. Their study tested two mechanisms that could possibly achieve this with the following hypotheses:

1. The ODCs are linked by axons of horizontal neurons that project mono-synaptically from the right-eye to non-adjacent left-eye ODC. The further apart the ODCs, the longer the axon and hence, the connecting axons in strabismics with ARC should be longer than in non-strabismics. In this situation the probability of developing ARC would not be related to angle of deviation until an upper limit was reached equal to the maximum axon length.

2. ODCs are linked by a chain of horizontal neurons, the number of which increases as the distance of corresponding ODCs increases. In this case the axon length in strabismics would be the same as non-strabismics. Therefore the larger the angle of strabismus the more horizontal neurons and synapses would be required to create the link between remote ODCs. The quality of the signal would be degraded such that the probability of developing ARC would be inversely proportional to the angle of deviation.

Of the three strabismic macaque monkeys studied, two had naturally occurring esotropia, one with presumed ARC and one without ARC, based on a small and large deviation respectively. The third monkey had a small esotropia induced by alternate occlusion of the eyes from birth to nine months of age. This monkey was also presumed to have ARC on the basis that the angle of deviation increased on dissociation, i.e. a small esotropia existed with a large latent component. The two non-strabismic monkeys served as control subjects.

Wong, Lueder, Burkhalter and Tychsen (2000) found no significant difference in the length of axons between the strabismic and non-strabismic monkeys hence, the first hypothesis was rejected in favour of the second. The mean axon length found was approximately 7mm. Clinical results, which showed an inverse relationship between

size of deviation and quality of binocular responses in the 192 strabismic children, were taken to confirm the second hypothesis. As ARC occurred most frequently in deviations of less than 10Δ the authors concluded that this fits with the neuroanatomy of V1, requiring just one or two axons, each approximately equal to 7mm, to connect ODCs representing anomalously corresponding points from each eye.

The inherent problem of drawing conclusions about the human visual system from animal studies is that it is impossible to be sure that these animals actually had ARC and anomalous BSV. In humans it is not uncommon to clinically find a small strabismus or an angle that increases on dissociation without demonstrable ARC. This is evident in several subjects studied in this thesis.

Strabismics with ARC show enhanced binocular responses when tests involving visual motion, (Wade 1976; Pöppel, Stoerig, Logothetis, Fries, Boergen, Oertel & Zihl, 1987) or perception of motion-in-depth (Sireteanu, Fronius & Singer, 1981; Kitaoji & Toyama, 1987) are utilised, rather than static tests. This has led to the suggestion that extrastriate cortex (where motion processing occurs) may be the site of physiological changes in ARC.

Cynader, Gardner and Mustari (1984) investigated responses to binocular visual stimulation in area 18 of normal cats and cats with surgically induced exotropia early in life. In normal cats 58% of units were binocularly activated by stimulation to either eye. A significant difference was seen in the exotropic cats, where only 10% of units were activated by stimulation of either eye and the majority of units were driven mainly by one eye, but not both eyes. An interesting, but rare, finding was that receptive fields of binocular neurons were located on non-corresponding points. The study provides evidence for some degree of re-mapping of the retinae onto the visual cortex, in the case of unilateral exotropia. The authors emphasise, however, that anomalously located receptive fields were found in only three of the seven animals studied. Additionally, when background neural activity could be evoked from stimulation of each eye in these three animals, it was mainly located in corresponding points in the two eyes.

A more localised area of cat's extrastriate cortex was investigated by Grant and Berman (1991). They examined receptive field positions of neurons in the motion-sensitive lateral suprasylvian (LS) area of extrastriate cortex in surgically induced esotropic cats. All strabismic cats examined had a major loss of binocularly driven cells in area 17. The few remaining binocularly driven cells had receptive field pairs from positions of NRC

in the two retinae. In area LS the effects on binocularly driven cells were dependent on the magnitude of strabismus. In the four cats with large esotropia (>18°) a loss of binocularity occurred in area LS equivalent to that in area 17. Those with moderate esotropia (11-15°) showed only a small breakdown of binocularly driven cells, whilst the group with small angled esotropia (≤10°) had normal proportions of binocular neurons. Additionally, they demonstrated a shift in receptive field position, with visual inputs arising from anomalous retinal locations such that anomalous binocular vision could exist. They postulate that a similar mechanism could be the basis for ARC and anomalous binocular vision demonstrated clinically in humans with small angle strabismus. The majority of LS neurons in cats are sensitive to the speed and motion of visual stimuli (Spear & Baumann, 1975; Blakemore & Zumbroich, 1987) and to motion-in-depth stimuli (Toyama & Kozasa, 1982). If a similar mechanism exists in humans then areas of the extrastriate cortex with a role in motion perception, i.e. V5, would be involved. The difficulty in this study of comparisons made with cats is that the areas involved are not anatomically similar to humans.

A later study by Sireteanu and Best (1992) revealed a similar adaptive shift of receptive field locations in response to surgically induced strabismus in the LS of cats. The disparities of the shifted fields were larger, ranging from 12 to 37°, which would be difficult to relate directly to ARC found clinically in humans, as it is typically demonstrable in angles <10°. Also only 6% of cells were found to have receptive field shifts in this study, which makes the likelihood of this forming any robust binocular interaction unlikely. This is obviously difficult to prove conclusively in cats.

Wong, Lueder, Burkhalter and Tychsen (2000) reject the evidence that the neuroanatomic mechanism for ARC resides outside V1. The reasons for this are as follows:

1. Fifty percent of binocular connections in V1 of naturally strabismic monkeys remain (Tychsen & Burkhalter, 1995).
2. The clinical-neuroanatomic correlation that strabismus of between 2 and 5° have the highest likelihood of developing ARC, which corresponds to one or two neuron lengths in V1, making this a possible site for such neural connections.
3. Receptive fields in extrastriate areas are much larger than V1. As axon lengths in the visual cortex do not vary from area to area and were found to be approximately 7mm in length. This would mean that such axons in extrastriate would link the foveola of the right eye with an eccentric point 40° from the foveola of the left eye. Hence large

angle strabismus would be just as likely to produce ARC as small angle strabismus, which is not found clinically.

1.4.8 Suppression and ARC: Consequence or cause of strabismus?

The question still remains as to whether suppression and ARC are the consequence of primary strabismus, or whether they are the primary defect, which results in strabismus. The finding that children with acquired strabismus report diplopia initially, with suppression developing later, suggests that suppression is a consequence of strabismus. It may be that a different mechanism exists in early onset strabismus in that suppression exists initially, as postulated by Gobin, (1968), and strabismus results. It is generally believed through clinical experience that ARC develops in children who have longstanding, small angle, stable strabismus, suggesting a gradual adaptation to the primary strabismus. It is difficult to diagnose the type of retinal correspondence in young children, as accurate subjective responses are required. The presumed gradual onset of ARC may therefore purely reflect the onset of reliable subjective responses at this later age.

Although cortical differences in monkeys have been found in the presence of surgically induced and naturally occurring strabismus, it is unknown whether they existed prior to strabismus or whether they resulted due to abnormal visual experience with strabismus.

1.5 Aim of thesis

The aim of this thesis is to determine how binocular status affects the control of saccadic eye movements, in particular, to demonstrate whether information from a suppressed eye is used for generating saccadic eye movements.

In order to perform experiments in subjects with strabismus where targets could be presented to one or both eyes whilst the fixation target was visible to both eyes, a novel method of dissociation was developed and is described in Chapter 2.

Chapter 3 tests the equipment used to generate saccadic stimuli and present targets to each eye. Experiment 1 determines whether a mirror galvanometer used to move the fixation target produces suitable saccadic stimuli and Experiment 2 determines the effectiveness of the shutter system designed as a method of dissociation.

The remote distractor effect described by Walker, Deubel, Schneider and Findlay (1997) motivated Experiment 4 of Chapter 5. This study is replicated in subjects with normal BSV using distractors along the horizontal axis presented to both eyes, to determine the effect of distractors on saccade latency and gain. The results are compared with distractors presented to the dominant eye or non-dominant eye during binocular viewing of the target. This determined whether the effects of binocular distractors on saccade generation are greater than monocular distractors and whether the dominant eye has greater influence over saccade generation than the non-dominant eye.

The same experiment is repeated in Chapter 6 in subjects with strabismus. Experiment 5 compares binocular and monocular distractors in subjects with strabismus with no potential BSV and suppression of the deviating eye. The aim is to determine whether distractors presented within the suppression area of the deviating eye affected saccade latency and gain. The effect is compared with distractors presented to the fixing eye. As a greater effect was found with binocular distractors compared to monocular distractors in the BSV subjects (Experiment 4) this was also explored with suppression to further establish whether the strabismic eye contributes to saccade generation.

The strabismic subjects with suppression claimed to be unaware of the distractor when it was presented to the strabismic eye. This is explored further in Experiments 6 and 7. They are designed to test whether the subjects are able to detect the distractor under this condition and also to determine whether the subjects are able to identify the location of the distractor despite being unaware of its presence.

To test whether the sensory adaptation of ARC in strabismus affects saccade generation the distractor experiment is repeated in Experiment 8 of Chapter 6 in subjects with clinically demonstrable anomalous BSV. It is expected that, as the distractor was visible when presented to the deviating eye in these subjects, latency and gain will be affected under this distractor condition. The hypotheses test whether the effect of distractors in the strabismic eye in ARC were similar to the monocular response in normal BSV and whether the location of the effect is shifted due to a change in retinal projection.

The distractor experiments determine how peripheral targets within the suppression area are used to generate saccades. Experiment 9 of Chapter 7 is designed to test how the point of central fixation of the strabismic eye contributes to saccade planning in subjects with suppression. A study of disconjugate adaptive control is performed to determine how manipulation of the fixation target affects saccades in BSV and strabismus with

suppression. Disconjugate saccade adaptation is induced by an electronic feedback system applied to a target visible to one eye. Comparisons of the response in normal bifoveal BSV and strabismus with suppression are made to determine whether the suppressing eye conveys information to stimulate the appropriate adaptive control process.

Chapter 2

Materials and methods

Provided in this chapter is a description of the equipment and laboratory set-up used to measure eye movements and to present targets to each eye independently.

2.1 Eye movement recordings

Horizontal eye movements were recorded using a Skalar IRIS 6500 infrared limbal tracker manufactured by Skalar Medical, Delft, The Netherlands. For a full description of this method see Reulen, Marcus, Koops, deVries, Tesinga, Boshuizen and Bos, (1988). This non-invasive method uses low powered light emitting diodes (LEDs) (filtered to remove visible light, leaving only the infrared part of the spectrum) to illuminate the external surface of the eye. The brightness of the reflected beam is measured. Infrared LEDs and infrared light sensitive detectors are positioned in front of the eyes mounted on a lightweight helmet as shown in Figure 2.1. The sensors' receptive fields cover the iris-sclera transition on both the nasal and temporal sides. As the eye rotates horizontally, for example to an abducted position, the temporal detector will measure a decreased infrared reflection and the nasal detector will receive an increased scleral reflection, see Figure 2.2. The subtracted nasal and temporal detector signal is converted into a voltage and once calibrated represents eye position with respect to head position. The resolution of this device is 0.03° and it has a linear recording range of ±20° (Reulen, Marcus, Koops, de Vries, Tesinga, Boshuizen & Bos, 1988). The analogue output from the Skalar IRIS 6500 was passed through a low pass 100Hz cut-off filter, to reduce mains noise, digitised to 12-bit resolution and sampled at 5ms intervals (200Hz).

The eye movement recorder was calibrated by presenting a sinusoidal pursuit stimulus that moved horizontally on the projection screen. The amplitude of the stimulus could be varied up to ±20° depending on the nature of the experiment. The calibration took 12.5 seconds during which time the target moved through 4 cycles at 0.32Hz. The subject was instructed to follow the target as accurately as possible. Eye position was then plotted against target position, for each eye, to ensure linearity of the recording and sufficient gain of the signal to provide adequate resolution (see Figure 2.3b). If linearity was not achieved the sensor heads were adjusted, the gain of the Skalar amplifier was

reduced or if still no improvement the amplitude of the stimulus was reduced. Calibration was then repeated. An example of the calibration graphs is shown in Figure 2.3. Runs of 50 seconds were recorded and calibrations were repeatedly performed after every fourth run of experimental conditions or earlier if any head movement occurred.

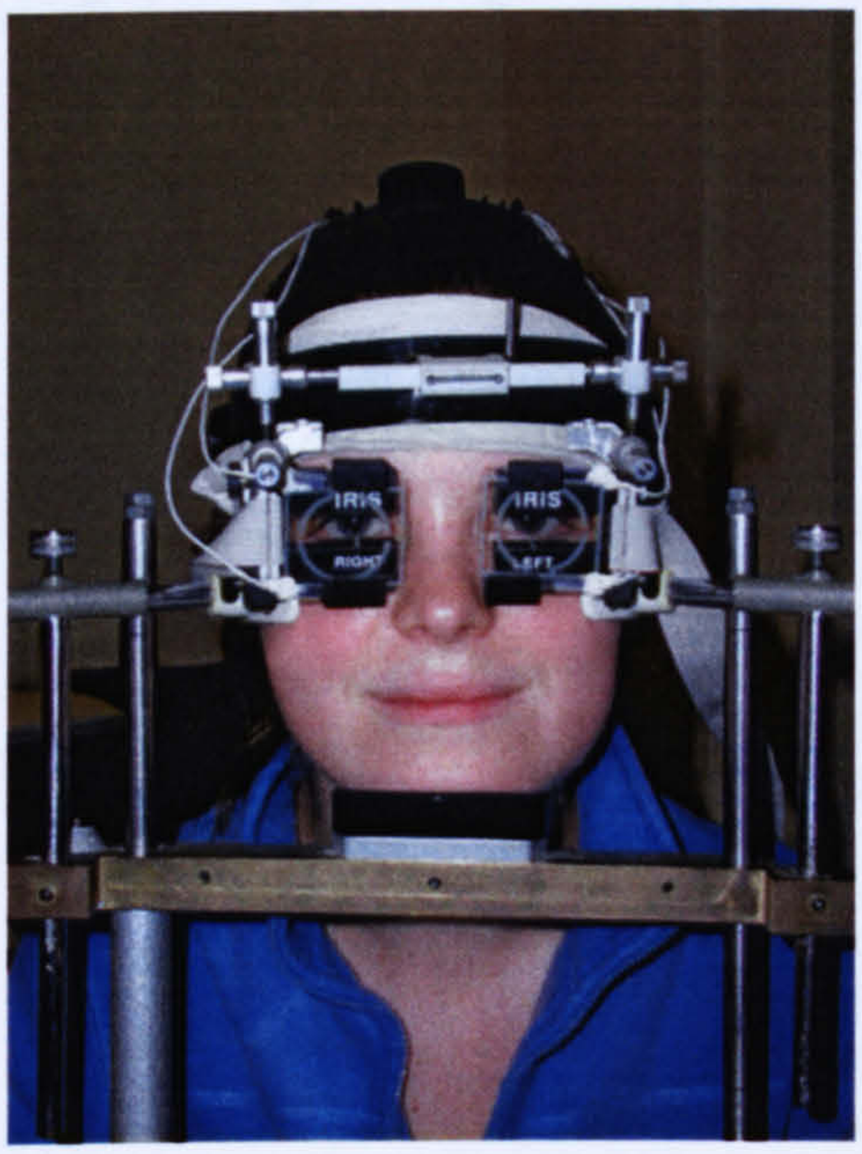


Figure 2.1: Subject wearing helmet containing the Skalar infrared eye tracker and LCP shutters mounted in front of each eye. Head stabilised using head-rest with adjustable chin and cheek rests.

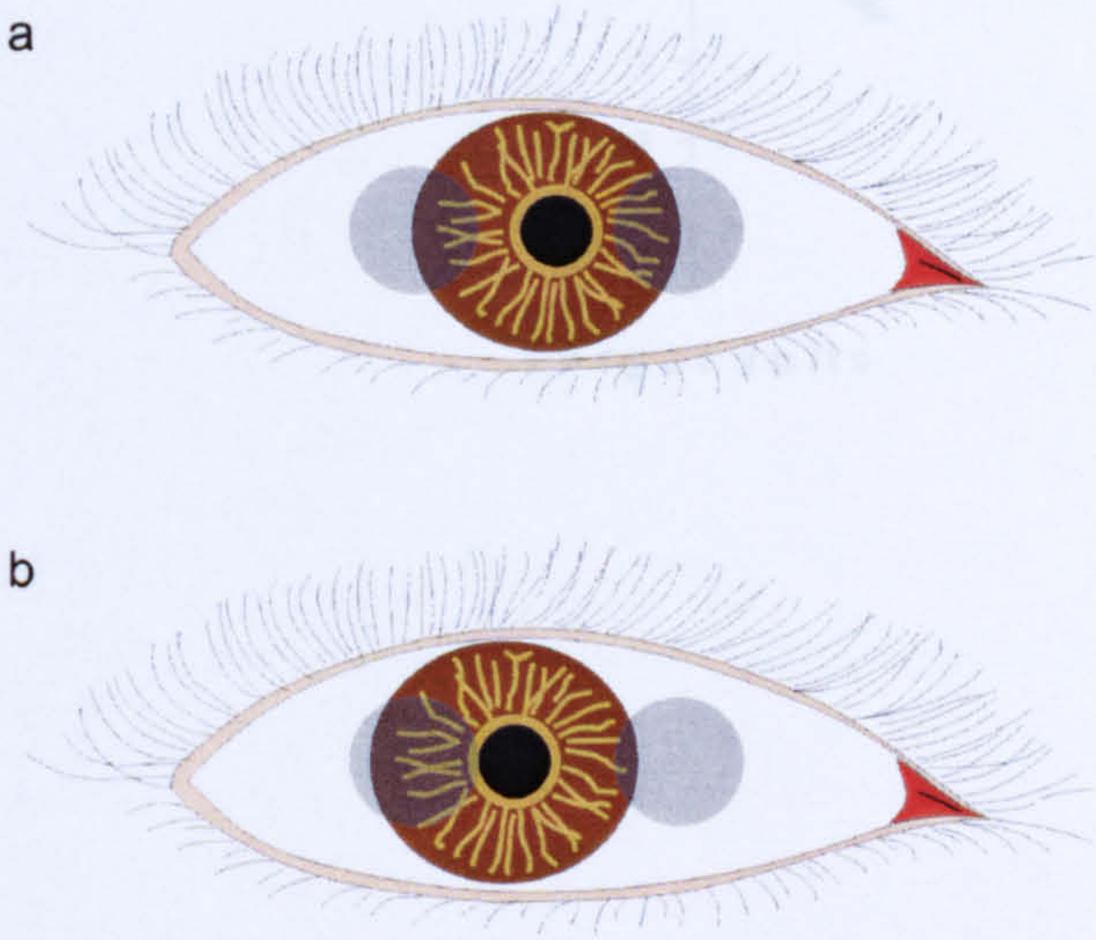


Figure 2.2: Principle of infrared eye movement recording. a) Right eye positioned in the midline, infrared light source is directed at the iris sclera transition on the nasal and temporal side. b) Right eye moved into an abducted position, the nasally positioned detector receives an increased reflection from the sclera, whilst the temporal detector receives a decreased reflection.

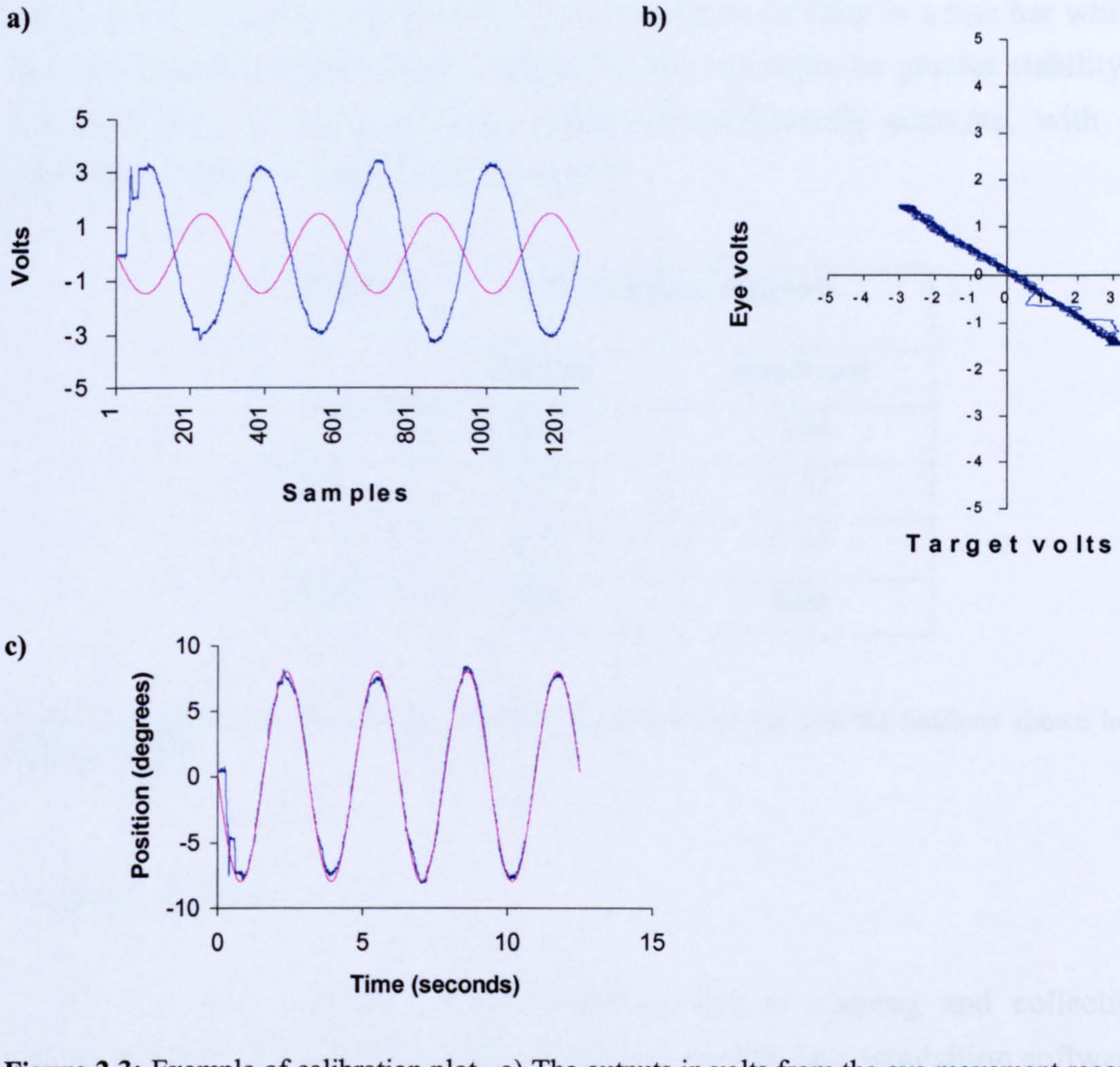


Figure 2.3: Example of calibration plot. a) The outputs in volts from the eye movement recorder (shown in blue) and mirror galvanometer (shown in pink) were sampled at 10ms intervals and plotted at each sample. The amplitude of the target movement was measured directly to allow target volts to be converted to degrees. b) The outputs from the eye movement recorder were plotted against the output from the mirror galvanometer. Inspection of the plot shows a linear relationship between eye and target position. The gradient of the linear regression best fit was found, allowing the output from the eye movement recorder to be converted into degrees. Calibrations were repeated if a non-linear relationship was found, if the target was not followed well, or if there were excessive blinks. The spurious signals are due to the eye making saccades at the start of the calibration as the eye catches up with the target. These can also be seen in a and c. c) The eye and target position traces were calibrated into degrees and plotted against time to ensure that an adequate fit was obtained. Data from strabismic subject 4, Experiment 3, Chapter 4.

2.2 Head stabilisation

Subjects were seated in a comfortable office chair, with their eyes 114cm from the flat back-projection screen. Their head position was stabilised using a chin-rest, forehead support and additional pads that rest against the cheekbones of the face as previously shown in Figure 2.1. This arrangement ensured adequate control of head position necessary to measure eye movements. Subjects were instructed to keep their head as still as possible but if required they could move their head from the chin rest at any time, although this would invalidate the test run. Table 2.1 shows that this system of

head fixation has been found to deliver comparable stability to a bite bar whilst making eye movements (Whittle 2002). Whilst the bite bar achieves greater stability the head-rest is within 0.2° and therefore considered sufficiently accurate, with the added advantage of greater comfort for the subject.

Subject	**Head rotation (degrees)**	
	Bite bar	**Head-rest**
1	0.38	0.64
2	0.23	0.50
3	0.16	0.25
Mean	**0.26**	**0.46**

Table 2.1: Average head movements recorded using a bite bar and the headrest shown in Figure 2.1, (Whittle, 2002).

2.3 Data collection

A PC was used to control target position, shutter opening and collection of eye movement data. Viewdac®, a commercially available data acquisition software package (Keithley Instruments, Inc., Taunton, MA, USA), was used to generate target position signals, shutter combinations and collect the data. The computer had a 90MHz Pentium processor and was connected to a DAS 1600 analogue to digital converter.

2.4 Analysis of saccades

Eye movement recordings were saved on disk and analysed after the testing session. Saccadic eye movement data was analysed using custom written Visual Basic computer software. Saccades were detected using acceleration criteria, which defined the start of a saccade as occurring when eye acceleration exceeded a pre-set value determined from an examination of the acceleration values of the whole eye movement trace. The trigger acceleration was set to be twice the noise level. The end of the saccade was identified using the same method but with a deceleration criteria. Each identified saccade was then checked visually on screen to confirm correct detection of the primary saccade by excluding clearly predictive saccades or errors due to loss of fixation. Data of saccade latency, peak velocity and saccade amplitude was then transferred to an Excel worksheet for further analysis.

2.5 Target presentation

Figure 2.4 shows a schematic diagram of the laboratory set-up. Two targets could be displayed on a large flat back projection screen (245 x 76cm) using two modified Kodak Carousel slide projectors situated 114cm behind the screen. Targets were produced as glass mounted slides and could be moved on the screen along the horizontal axis using mirror galvanometers (General Scanning, Banbury, UK) mounted close to the front of each projector lens. The modification of projectors included cutting away part of the projector body to make space for mounting the mirrors, mounting of the mirror galvanometers close to the front of the projector lenses to capture the maximum amount of light and fitting of two shutter systems described in further detail below. It was important that the targets from both projectors 1 and 2 (see Figure 2.4) were similar in size and appearance for experiments in Chapter 7. Each projector had the same internal optics and new bulbs were carefully fitted and focussed to produce images of similar colour and luminance. Luminance was approximately matched with the addition of a neutral density filter to one projector.

Presentation of the targets onto the screen could be controlled using two methods; 14mm aperture metal shutters (Uniblitz, Optilas LTD, Milton Keynes, UK) or liquid crystal polymer (LCP) shutters (Phillips Optics, Eindhoven, The Netherlands, see Section 2.6). These two shutter systems were mounted either side of the projector lens as schematically shown in Figure 2.4. The metal shutters were mounted at the focal point in the illumination system of the slide projectors and the LCP shutters were strapped to the front surface of the projector lens. The metal shutters were used for controlling presentation of the targets on the screen (Chapter 3, Experiment 3.2 only), whereas the LCP shutters operated silently at a high frequency to allow dissociation of the eyes (Chapters 5, 6 & 7).

A third projector, also positioned centrally behind the screen, was used to present a stationary background if required in the experiments (projector shown positioned obliquely in Figure 2.4 for clarity).

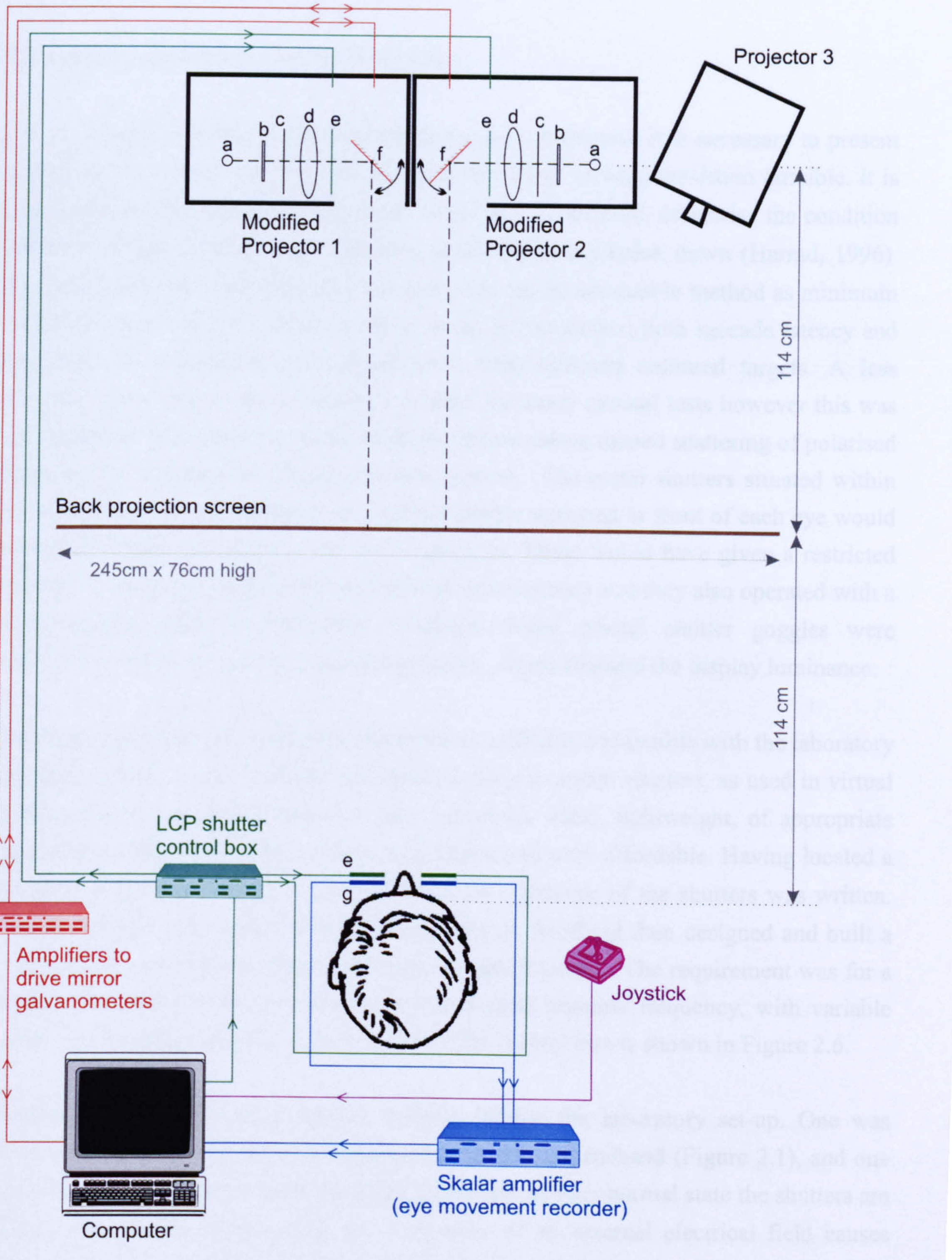


Figure 2.4: Schematic diagram of laboratory set-up.

2.6 Liquid crystal polymer shutter system

To investigate binocular vision and suppression in strabismus it is necessary to present images to each eye separately, but in the most natural viewing condition possible. It is important that the level of dissociation to the eyes is minimal, otherwise the condition under investigation (binocular vision or suppression) can break down (Harrad, 1996). Red and green filters to dissociate the eyes were not an acceptable method as minimum dissociation was required and, in a pilot study by the author, both saccade latency and accuracy were found to vary significantly with different coloured targets. A less dissociative method using polarisation is used for many clinical tests however this was not suitable in this instance, as the back projection screen caused scattering of polarised light due to the random translucent fibre content. The metal shutters situated within each projector were unsuitable, as a similar shutter mounted in front of each eye would have been impractical due to the small apertures. These would have given a restricted field of view and an undesirable step change in luminance and they also operated with a loud audible click. Commercially available liquid crystal shutter goggles were considered, however these contained a polarisor, which reduced the display luminance.

As there was no suitable system of dissociation available compatible with the laboratory projector set-up, a new method was required. Liquid crystal shutters, as used in virtual reality systems, were considered as they are rapid, silent, lightweight, of appropriate size, had a high transmission of light when open and were affordable. Having located a suitable shutter (Figure 2.5), a specification for operation of the shutters was written. The Department of Medical Physics, University of Sheffield then designed and built a control system for the shutters to the required specification. The requirement was for a system that would run four shutters, at the highest possible frequency, with variable phase and opening duration. A photograph of the control box is shown in Figure 2.6.

Figure 2.4 shows the LCP shutter locations within the laboratory set-up. One was positioned in front of each eye, mounted on the Skalar headband (Figure 2.1), and one in front of each lens of the two modified projectors. In their normal state the shutters are highly transparent (Figure 2.5), but application of an external electrical field causes them to turn instantly turbid, scattering light and hence closing the shutter (Figure 2.7). The shutters operate silently and with a 1ms response time. They were controlled by the computer via the control box, which ran all four shutters at a constant frequency of 80Hz. This frequency was used since a lower frequency, such as <60Hz, would give rise

to visible target flicker, and a higher frequency, such as >100Hz would reduce target luminance.

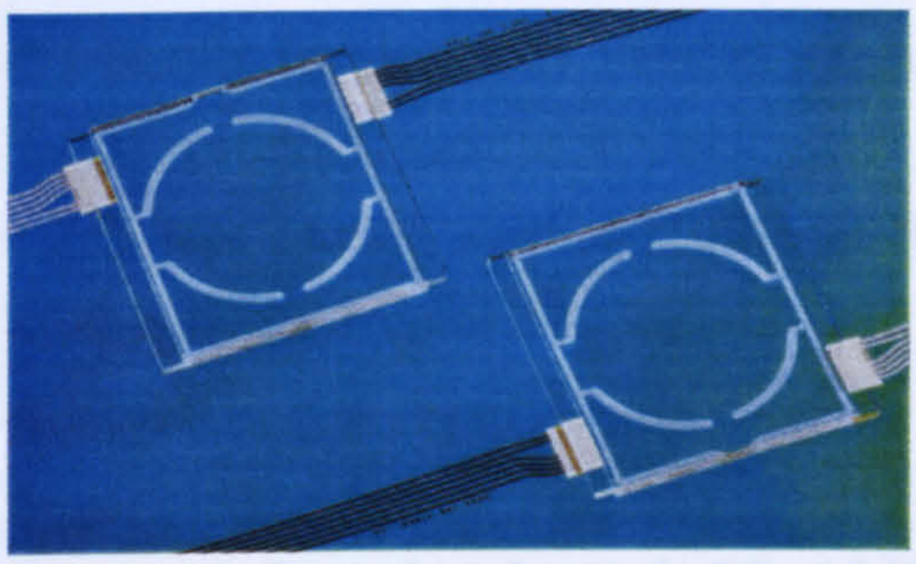


Figure 2.5: Liquid crystal polymer shutters used to present targets to each eye (Phillips Optics, Eindhoven, The Netherlands).

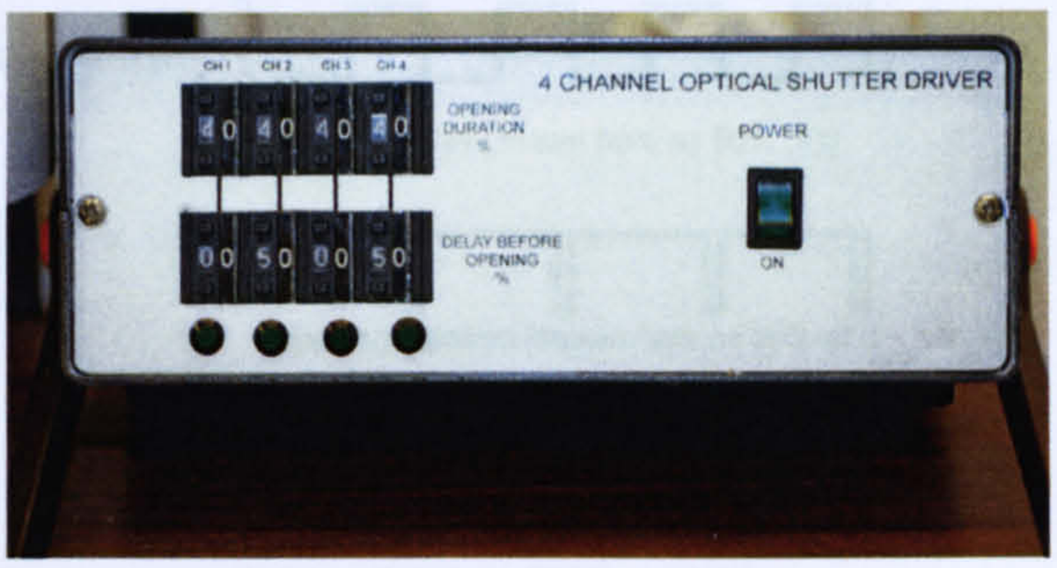


Figure 2.6: Photograph of LCP shutter control box.

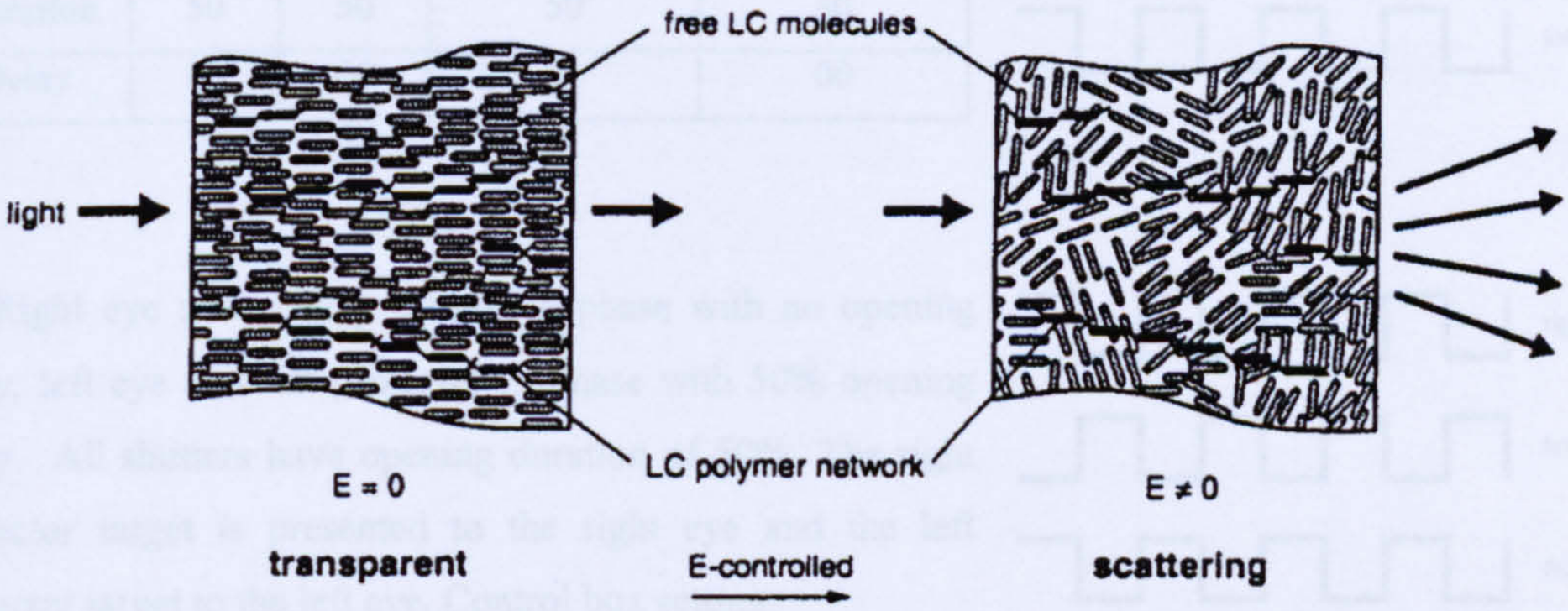


Figure 2.7: Schematic diagram of the Liquid crystal polymer shutters

2.6.1 Control of shutters

The 80Hz square wave signal could be adjusted by two factors using the control box; opening duration (10-100%) and opening delay (0-90%) for each of the shutters (Figure 2.8). These variables allowed sufficient control over shutter openings in relation to each other, which, in certain conditions, could enable dissociation of the eyes. Figure 2.9 shows examples of shutter synchronisation. The computer was programmed in Viewdac® for each experiment, to apply the appropriate electrical signal to open the correct shutter combinations, synchronised to the target as required.

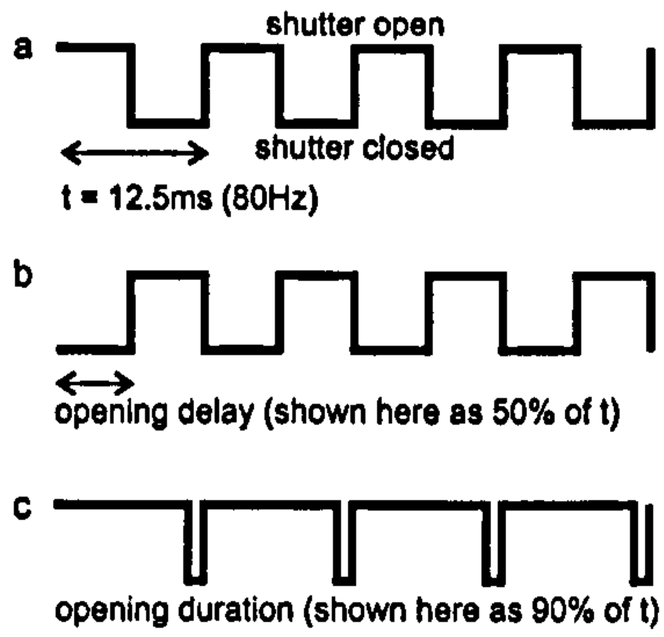


Figure 2.8: LCP shutter control box variables;

(a) 80Hz square wave signal generated by the LCP shutter control box.

(b) Shutter opening delay (0-90%) i.e. signal phase shift, shown here as half cycle or 50% of t.

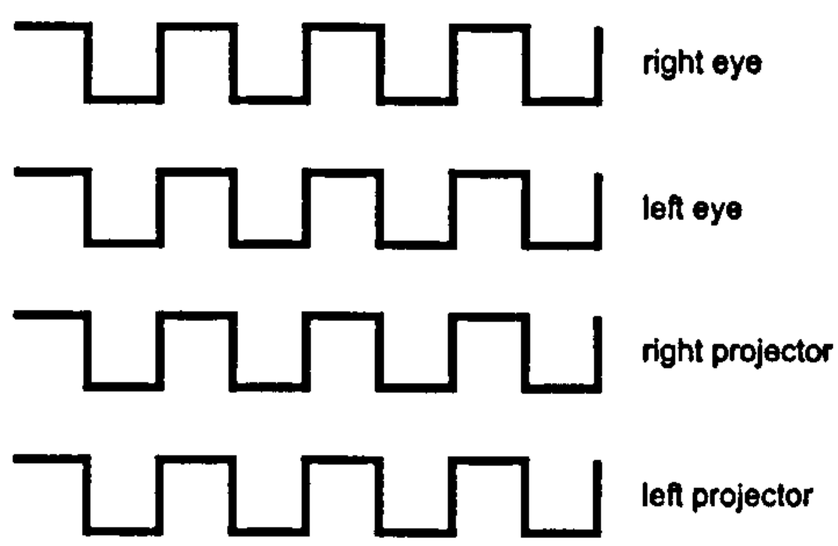
(c) Shutter opening duration (10-100%) shown as 90% of cycle with shutter open.

(t = time)

Figure 2.9: Examples of control of the 4 LCP shutters.

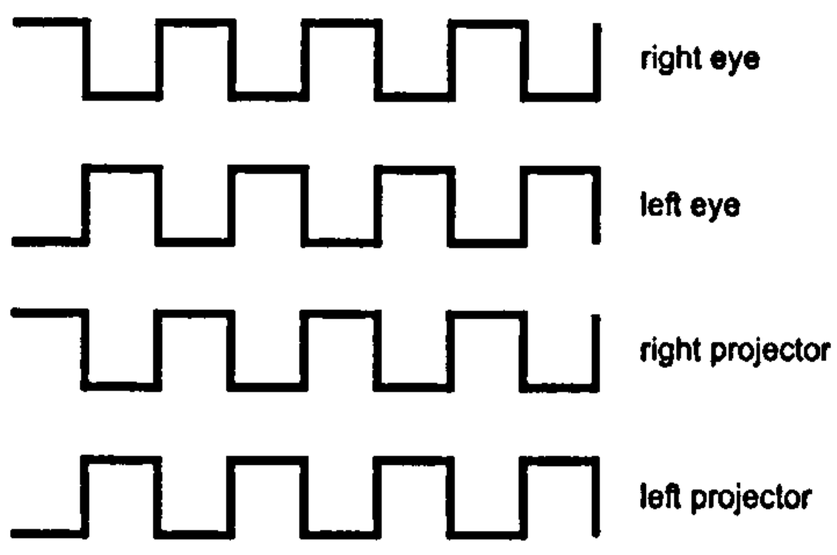
(a) All 4 shutters in phase = no opening delay and 50% opening duration. This will give both targets presented to both eyes. Control box setting:

%	RE	LE	R projector	L projector
Duration	50	50	50	50
Delay	00	00	00	00



(b) Right eye and right projector in phase with no opening delay, left eye and left projector in phase with 50% opening delay. All shutters have opening duration of 50%. The right projector target is presented to the right eye and the left projector target to the left eye. Control box setting:

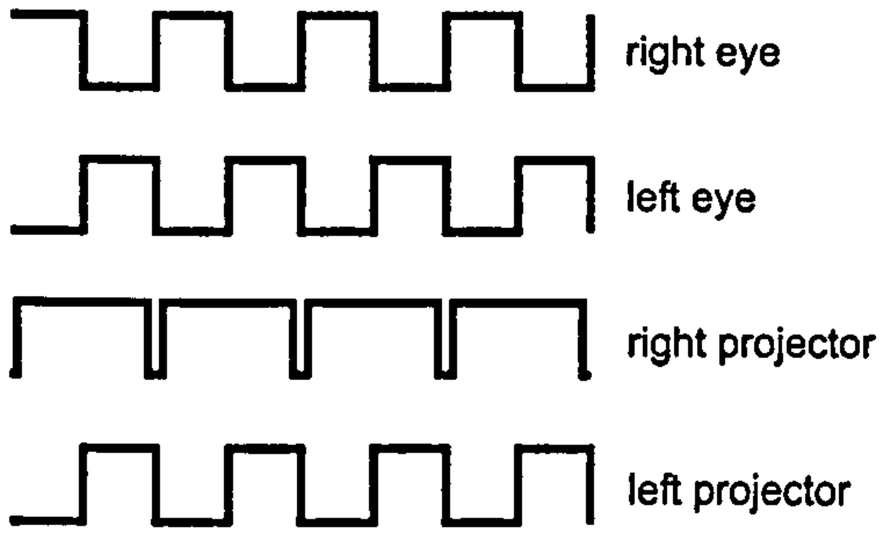
%	RE	LE	R projector	L projector
Duration	50	50	50	50
Delay	0	50	0	50



(c) Left eye and left projector in phase with 50% delay and 50% duration, right eye no delay with 50% duration. Right projector has 10% delay and 90% opening duration. Left projector target is therefore presented to the left eye only and the right projector target is presented to both eyes.

Control box setting:

%	RE	LE	R projector	L projector
Duration	50	50	90	50
Delay	0	50	10	50



2.7 Statistical analysis

Data was analysed using Excel spreadsheets and statistical analysis was performed using either Statview 5 statistical software, (SAS Institute Inc. NC. USA) or CLR ANOVA 1.12, (Clearlake Research, USA). Cited significance levels are those obtained after applying where necessary conservative epsilon corrections for departures from covariance homogeneity assumptions (Howell, 1992).

2.8 Ethics approval

As the study required recruitment of subjects with strabismus from the Royal Hallamshire Hospital eye department, Sheffield South Ethics Committee approval was obtained prior to commencing the study (Appendix 1).

In all experiments, procedures were explained to the subjects verbally and with written information sheets and, if willing to participate, they signed a consent form, approved by the ethics committee (Appendix 2).

Chapter 3

Preliminary experiments

This chapter describes the experiments carried out to validate the equipment and methods used in later experiments.

3.1 Experiment 1: To determine whether the mirror galvanometer produces targets suitable as saccadic stimuli

3.1.1 Introduction

This experiment was designed to test the suitability of the mirror galvanometer as a method of presenting saccadic stimuli for future experiments. The mirror galvanometer had a phase lag of 1ms for 1Hz sine wave signals of amplitudes between ±1° and ±10° (Whittle, 2002). It was possible, however that, as the mirror changed the target to a new position on the screen, the target moving rapidly across the screen was visible to the observer, which may have led to an alteration in saccade latency, accuracy and peak velocity. The experiment compared these saccade characteristics with and without masking of the translucent screen. The mask, a simple piece of cardboard with holes cut into it at the target locations, was used to eliminate any chance of the target being seen whilst moving between the target locations. However this mask was not suitable for use in the main experiments as many target locations were required and projection of backgrounds would not have been possible.

3.1.1.1 Hypothesis

There is no difference in saccade characteristics with or without masking of the screen.

3.1.2 Method

3.1.2.1 Participants

Four subjects, mean age 29.25 years (range 20 to 38 years), were recruited from the student population. They all had minimum visual acuity of 0.0 logMAR in each eye, normal bifoveal BSV and stereoacuity of ≥60" of arc with TNO test (Table 3.1 shows subject details).

Subject	Age	Gender	VA		Binocular status	Stereoacuity (seconds of arc)
			RE	LE		
1	20	F	0.0	-0.1	esophoria	60
2	27	M	-0.1	-0.1	exophoria	30
3	32	F	0.0	-0.1	exophoria	30
4	38	M	-0.1	0.0	exophoria	60

Table 3.1: Characteristics of the four subjects. VA = visual acuity in log MAR, RE = right eye, LE = left eye.

3.1.2.2 Apparatus

Figure 2.4 shows the laboratory set-up. Each subject was seated in front of the translucent screen at a distance of 114cm from the eye. Head movements were restricted by use of a chin and cheek rest. The target was back projected onto the screen and its position varied by a mirror galvanometer controlled by a pre-set computer programme. Figure 3.1 shows the target used, a circle of diameter subtending 1° with a cross in the centre. Eye movements were recorded as described in Chapter 2. A removable cardboard mask could be temporarily positioned to cover the rear surface of the screen, with the exception of 1.5° holes sited at the target locations, used to prevent any visibility of the target as it moved between target locations (Figure 3.2).

3.1.2.3 Design of the experiment

The experiment was repeat measures design, with the independent variable being the target presentation, with and without the screen mask. Dependent variables were the saccade latency, saccade gain and saccade peak velocity.

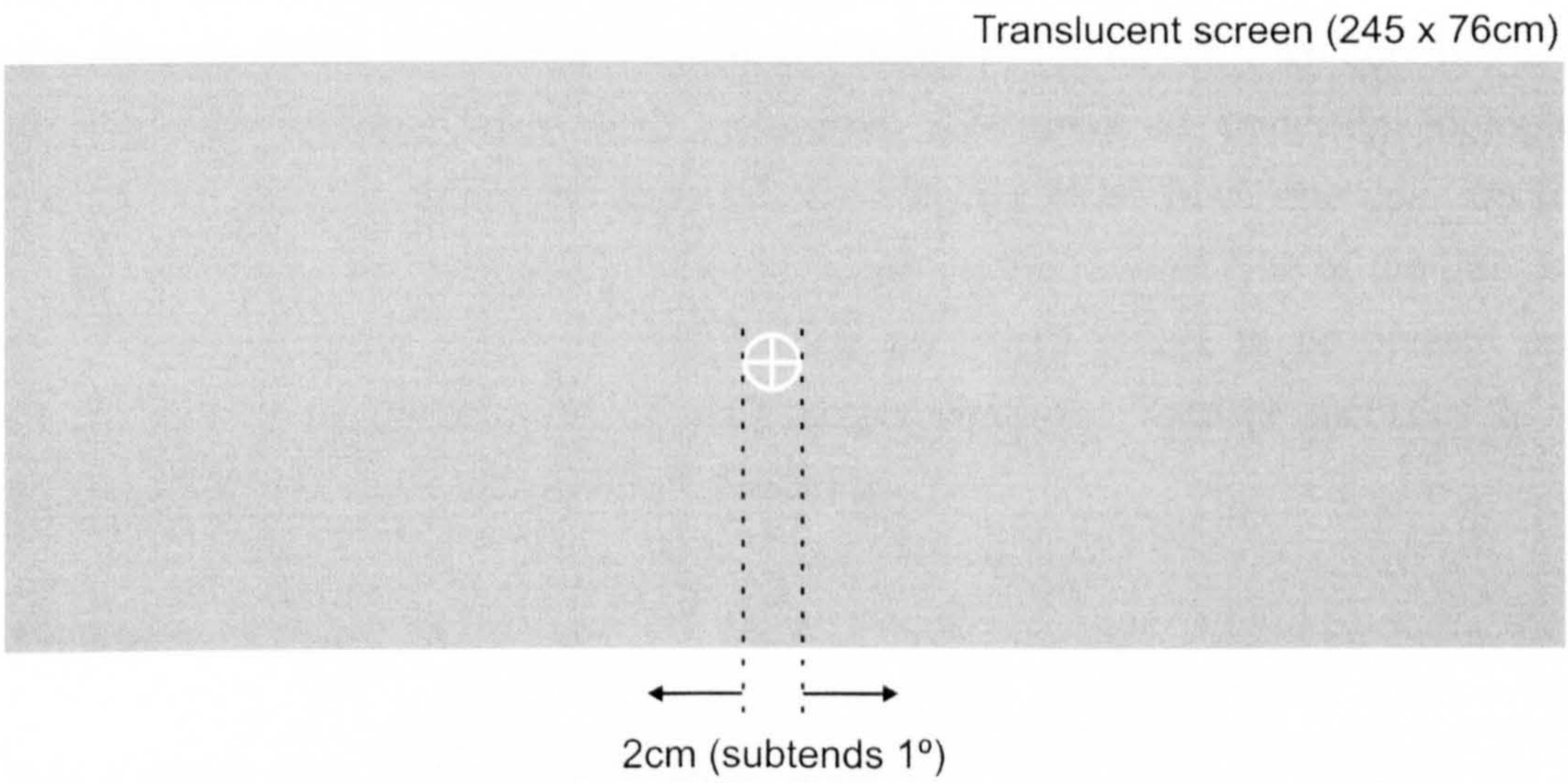


Figure 3.1: Schematic view of the target as it appeared on the translucent screen.

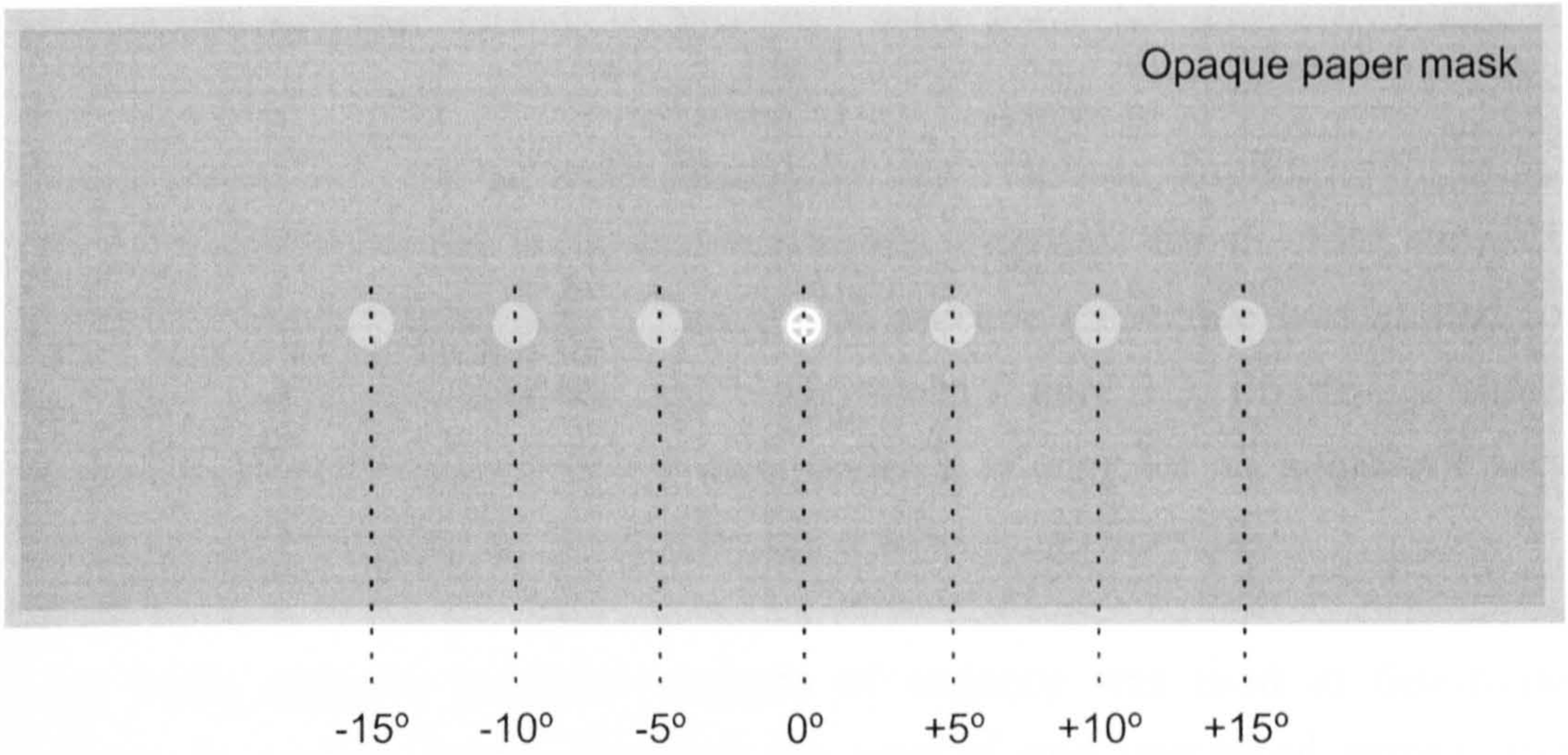


Figure 3.2: Schematic view of the mask in place behind the screen. The figure shows the holes (1.5°) in the mask, however these were not visible to the subjects.

3.1.2.4 Procedure

A calibration routine was carried out, without the mask, before each trial, during which subjects were asked to follow the target as it moved in a ± 20° sinusoidal waveform, as described in Chapter 2.

At the start of each trial the target stimulus was presented in the centre of the screen for a variable period of between 1.5 and 2s. The target was programmed to move in a pseudo-random order to amplitudes of -15, -10, -5, +5, +10 and +15°, negative values being to the left of centre and positive to the right. The time period at each position varied randomly between 0.5 and 1s. The subject was instructed to move their eyes as quickly and accurately as possible to fixate the centre of the target. Two conditions were tested, referred to as masked and unmasked. The masked condition completely eliminated the possible persistent image as the target moved from one position to the next. This was achieved by placing the paper mask on the reverse side of the translucent screen. The unmasked condition allowed the persistent image to be present on the screen as the mirror rotated to the new target position. Twenty saccades of each amplitude were performed for each test condition.

3.1.3 Results

All four subjects were included in the data analysis.

3.1.3.1 Saccade latency

Table 3.2a shows the mean saccade latency for each saccade amplitude, for individual subjects in the masked and unmasked conditions. The data for the four subjects was pooled, mean saccade latency as a function of saccade amplitude was plotted for the masked and unmasked conditions and is shown in Figure 3.3. Figure 3.4 shows the distribution of saccade latencies. The mean saccade latency for all amplitude saccades masked was 160.8ms (SD=11.1) and unmasked was 163.4 (SD=8.8).

A three factor repeated measures analysis of variance was used to determine any differences in saccade latency between the masked and unmasked screen, right or leftward saccades and the three amplitudes used. No significant difference was found between the masked and unmasked conditions [$F(1,3)=0.092$, $p>0.05$], right or leftward saccades [$F(1,3)=5.281$, $p>0.05$] or saccade amplitude [$F(2,6)=3.399$, $p>0.05$]. No significant interaction was found between any combinations of these three factors, specifically the masked and unmasked conditions (see Appendix 3.1 for statistical analysis).

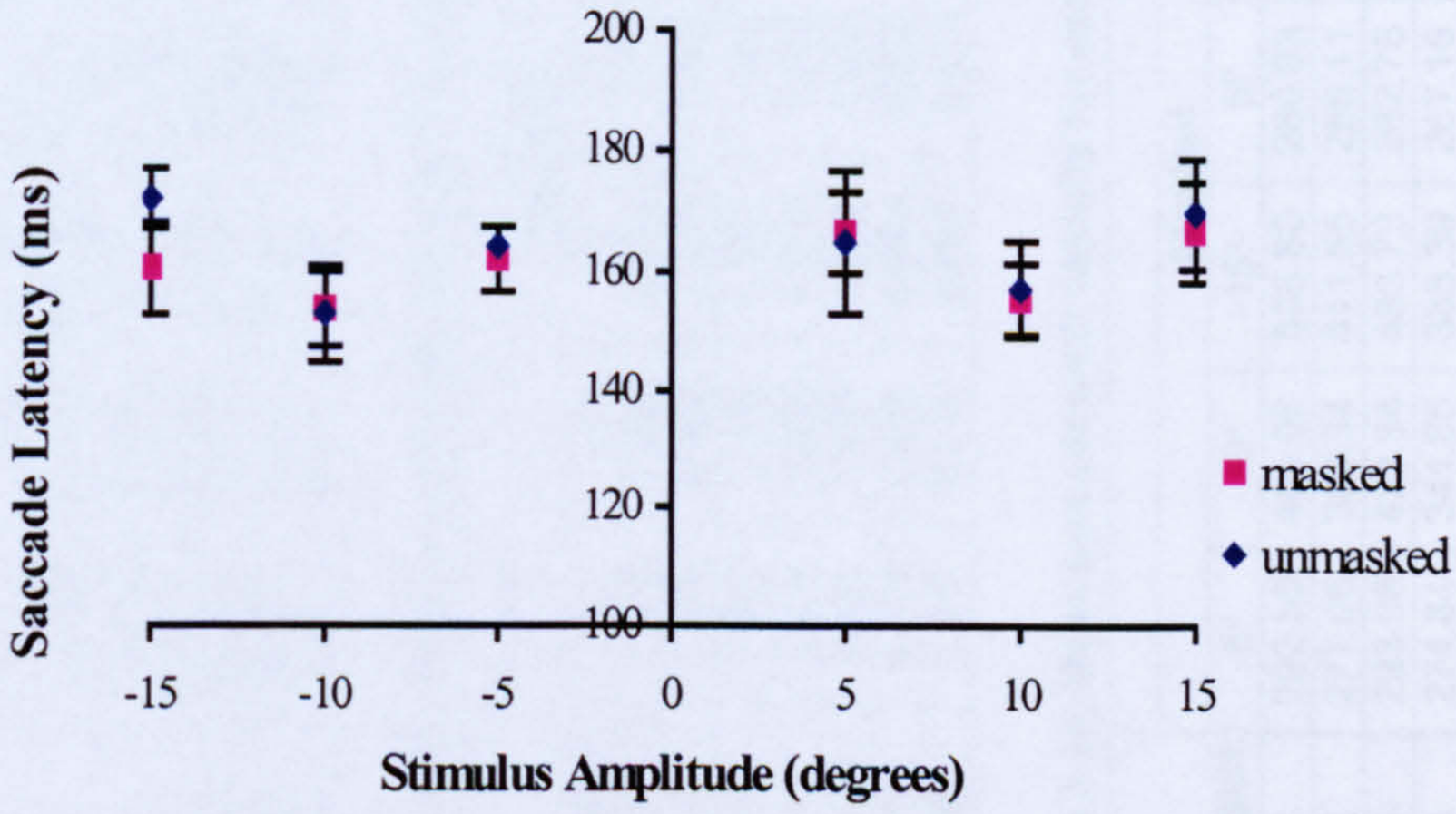


Figure 3.3: Pooled data of four subjects' saccade latency masked and unmasked. Error bars represent ±1 standard error from the mean.

Table 3.2a: Mean saccade latency for each saccade amplitude with and without masking of the screen.

	Saccade Latency (ms)											
	Masked						Unmasked					
Subject	-5°	-10°	-15°	5°	10°	15°	-5°	-10°	-15°	5°	10°	15°
1	152.05	143.65	141.64	148.50	141.33	143.40	132.83	136.06	134.81	133.74	138.83	143.31
2	170.50	164.75	173.25	179.70	164.25	168.53	181.36	164.25	182.25	190.88	177.69	172.24
3	172.58	164.50	154.50	165.63	166.17	182.08	180.50	169.00	163.00	167.68	156.64	180.60
4	153.32	142.20	172.71	171.75	149.75	171.5	161.85	142.24	170.73	166.50	154.83	181.50
Mean	**162.11**	**153.77**	**160.53**	**166.39**	**155.38**	**166.38**	**164.14**	**152.89**	**171.99**	**164.7**	**157.00**	**169.41**
SD	**10.93**	**12.54**	**15.31**	**13.25**	**11.89**	**16.38**	**22.73**	**16.18**	**9.69**	**23.49**	**15.95**	**17. 90**
SE	**5.47**	**6.27**	**7.66**	**6.62**	**5.94**	**8.19**	**11.36**	**8.09**	**4.84**	**11.75**	**7.97**	**8.95**

Table 3.2b: Mean saccade gain for each saccade amplitude with and without masking of the screen.

	Saccade Gain											
	Masked						Unmasked					
Subject	-5°	-10°	-15°	5°	10°	15°	-5°	-10°	-15°	5°	10°	15°
1	1.112	0.964	0.976	1.032	0.942	0.913	1.017	0.932	0.881	1.037	0.922	0.909
2	1.046	0.988	0.888	0.964	0.888	0.923	1.057	0.885	0.836	0.943	0.848	0.847
3	1.067	1.050	0.905	1.050	0.957	0.871	1.119	1.049	0.945	1.030	0.959	0.872
4	1.034	1.010	0.818	1.032	1.020	0.943	1.008	0.900	0.816	1.139	0.973	0.909
Mean	**1.065**	**1.003**	**0.897**	**1.019**	**0.952**	**0.913**	**1.050**	**0.942**	**0.870**	**1.037**	**0.925**	**0.884**
SD	**0.034**	**0.037**	**0.065**	**0.038**	**0.055**	**0.030**	**0.050**	**0.074**	**0.057**	**0.080**	**0.056**	**0.031**
SE	**0.017**	**0.018**	**0.032**	**0.019**	**0.027**	**0.015**	**0.025**	**0.037**	**0.029**	**0.040**	**0.028**	**0.015**

Table 3.2c: Mean saccade peak velocity for each saccade amplitude with and without masking of the screen.

	Saccade Peak Velocity (deg/sec)											
	Masked						Unmasked					
Subject	-5°	-10°	-15°	5°	10°	15°	-5°	-10°	-15°	5°	10°	15°
1	292.55	405.08	508.80	280.93	404.58	462.67	279.16	383.74	456.26	278.89	371.54	438.51
2	277.06	368.34	411.55	266.11	376.37	456.24	265.63	336.39	389.55	240.86	240.86	409.46
3	293.08	423.84	483.73	262.78	376.04	404.86	293.53	402.92	476.43	261.77	371.61	406.08
4	274.84	341.66	385.39	267.16	378.78	416.08	268.00	351.06	385.29	273.46	352.51	409.26
Mean	**284.38**	**384.73**	**447.37**	**269.25**	**383.94**	**434.96**	**276.58**	**368.53**	**426.88**	**263.75**	**334.13**	**415.83**
SD	**9.78**	**36.82**	**58.37**	**8.01**	**13.81**	**28.77**	**12.75**	**30.29**	**46.34**	**16.84**	**62.82**	**15.20**
SE	**4.89**	**18.41**	**29.18**	**4.00**	**6.91**	**14.38**	**6.38**	**15.14**	**23.17**	**8.42**	**31.41**	**7.60**

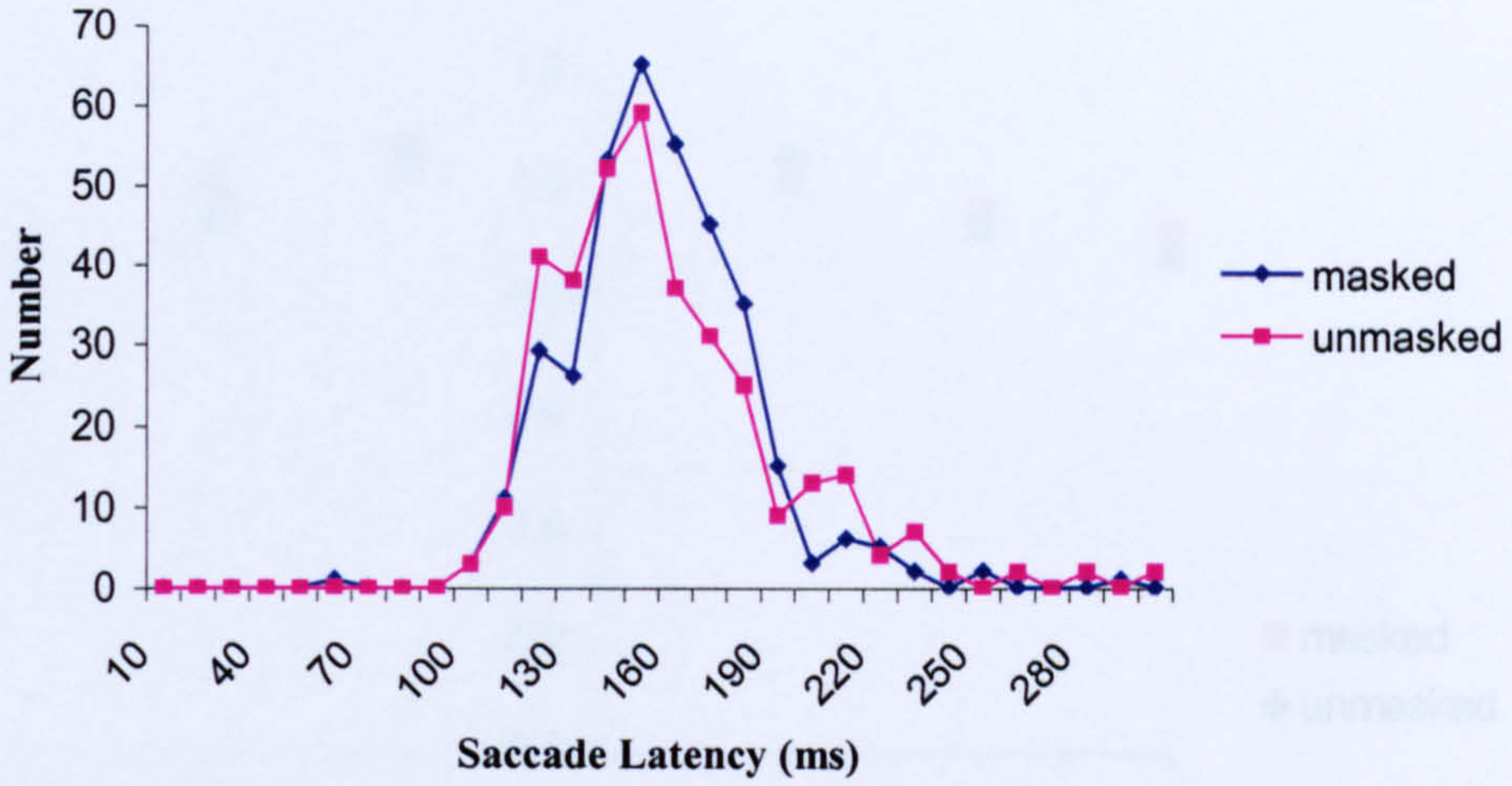


Figure 3.4: Distribution of saccade latencies for the four subjects - data includes 240 saccades from each subject.

3.1.3.2 Saccade gain

The accuracy of saccades was quantified by taking the gain, calculated as saccade amplitude divided by stimulus amplitude. Hence, a gain of 1 indicates a saccade which is precisely on target, a gain <1 indicates a hypometric saccade and >1 a hypermetric saccade.

Table 3.2b shows the mean saccade gain for all stimulus amplitudes for each subject, and the mean for the group in masked and unmasked conditions. Figure 3.5 shows the group mean saccade gain plotted as a function of stimulus amplitude. In both the masked and unmasked conditions 5° stimulus amplitudes in both directions produced very slightly hypermetric saccades, 10° left produced saccades close to the stimulus with a mean gain of 1.003, and 10° right slightly hypometric saccades. The degree of hypometria increased slightly for 15° stimulus amplitudes in both directions. This response was expected (Bartz, 1967; Becker, 1972).

A three factor repeated measures analysis of variance was used to determine any differences in saccade gain between the masked and unmasked conditions, right or leftward saccades and the three amplitudes used. No significant difference was found between the masked and unmasked conditions [$F(1,3)=3.068$, $p>0.05$] right or leftward saccades [$F(1,3)=0.268$, $p>0.05$]. The gain, as expected, was significantly different for saccade amplitude [$F(2,60=41.88$, $p<0.001$]. No significant interaction was found between any combinations of these three factors (see Appendix 3.2 for statistical analysis).

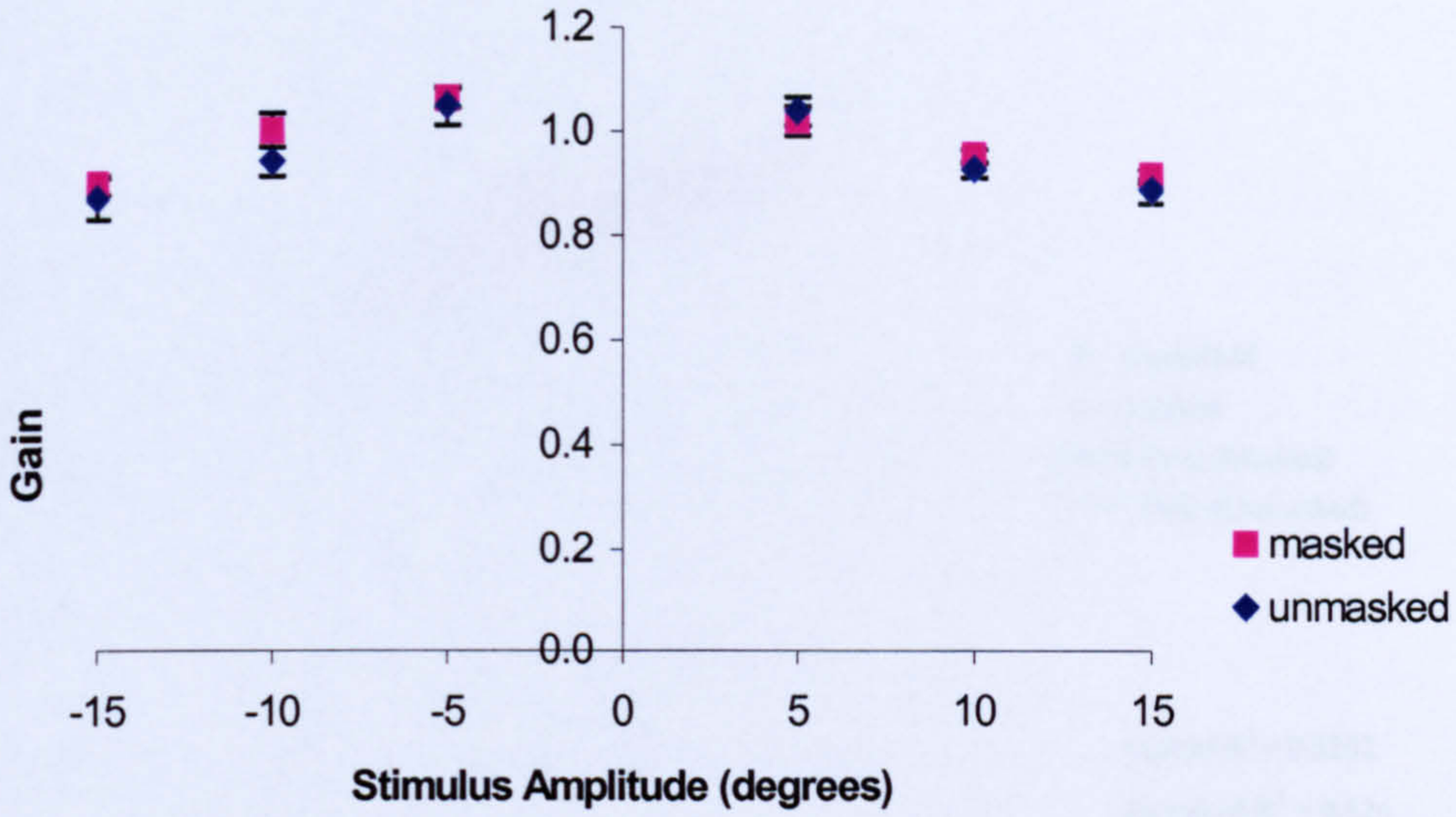


Figure 3.5: Pooled data of the four subjects' saccade gain, masked and unmasked, for each stimulus amplitude. Error bars represent ±1 standard error from the mean.

3.1.3.3 Saccade peak velocity

Table 3.2c shows the mean saccade peak velocity in the masked and unmasked conditions, for individual stimulus amplitudes, for each subject and the group mean. Figure 3.6 shows the log of the mean saccade peak velocity against log of stimulus amplitude for the four subjects. R^2 values for the masked and unmasked conditions are 0.8202 and 0.824 respectively. A three factor repeated measures analysis of variance was used to determine any differences in saccade peak velocity between the masked and unmasked conditions, right or leftward saccades and the three amplitudes used. No significant difference was found between the masked and unmasked conditions [$F(1,3)=4.142$, $p=0.1347$], right or leftward saccades [$F(1,3)=1.219$, $p>0.05$]. The peak velocity, as expected, was significantly different for saccade amplitude [$F(2,6)=104.892$, $p<0.001$]. No significant interaction was found between any of the three factors (see Appendix 3.3 for statistical analysis).

The saccade gain, latency and peak velocity were typical of values expected based on existing literature as outlined in Chapter 1. This is more specifically addressed in Chapter 4. The results support the hypothesis that there is no significant difference in saccade characteristics with or without masking of the screen.

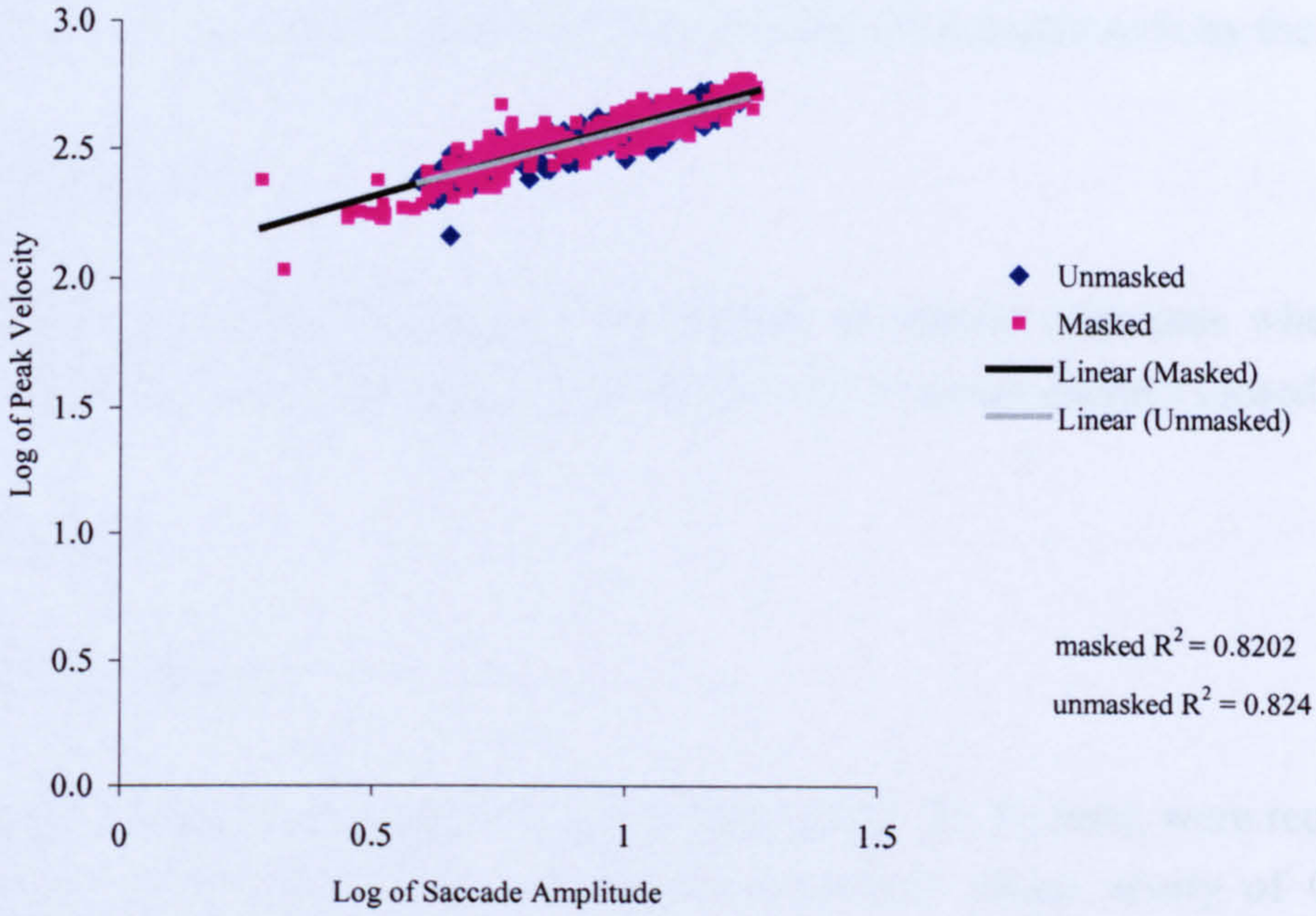


Figure 3.6: Pooled data for the four subjects. The log of peak velocity is plotted as a function of the log of saccade amplitude. A linear regression for the masked and unmasked conditions revealed similar R^2 values.

3.1.4 Conclusion

There were no significant differences between the masked and unmasked conditions for saccade latency, accuracy and peak velocity. It is therefore considered satisfactory to use the mirror galvanometer mounted to the slide projector to present saccadic stimuli in future saccade eye movement experiments.

3.2 Experiment 2: To determine the effectiveness of the LCP shutter system as a method of dissociation

3.2.1 Introduction

To study strabismus, suppression and retinal correspondence it is necessary to present targets to each eye independently whilst both eyes are open. As described in Chapter 2 a system of such dissociation was specifically designed for this thesis, using four liquid crystal polymer (LCP) shutters. This allowed each target on the screen to be visible by both eyes, right eye only, left eye only or invisible to either eye.

The experiment outlined below will determine whether this method of dissociation is effective or whether targets believed to be invisible are actually seen by the subject.

3.2.1.1 Hypothesis

There is a significant difference in the number of correct responses when targets are presented with all shutters open and either the LCP or metal shutters closed.

3.2.2 Method

3.2.2.1 Participants

Five adult subjects, mean age 20.4 years (range 19.0 - 21.9 years), were recruited from a student population, all having a minimum corrected visual acuity of 0.0 logMAR, normal binocular single vision, heterophoria <10 Δ and stereoacuity ≥60" of arc (see Table 3.3 for subject details).

Subject	Age	Gender	VA		Binocular status	Stereoacuity (seconds of arc)
			RE	LE		
1	19	F	0.0	0.0	exophoria	60
2	20	M	0.0	-0.1	exophoria	30
3	20	F	-0.1	-0.1	exophoria	60
4	20	M	-0.1	0.0	esophoria	60
5	21	F	0.0	-0.1	exophoria	60

Table 3.3: Characteristics of the five subjects.

3.2.2.2 Apparatus

Figure 2.4 shows the laboratory set-up used. Each subject was seated in front of the translucent screen at a distance of 114cm from the eye. Head movements were restricted by use of the chin and cheek rest. A target was back projected onto the translucent screen using a Kodak carousel slide projector. Figure 3.1 shows the target used, a circle of diameter subtending 1° with a cross in the centre. The target was back projected onto the screen and its position varied by a mirror galvanometer controlled by pre-set sequences via the computer. On-screen target presentation could be controlled by two methods; a) a LCP shutter, positioned between the lens and the mirror galvanometer of the projector, and b) metal shutters, positioned behind the lens of each projector. Two further LCP shutters were used, one positioned in front of each of the subject's eyes,

mounted on a headband. A blurred, random dot stationary background was also projected onto the screen using an additional projector. The background was not a requisite of this experiment, however it was used to create standard conditions planned for later experiments (see Chapter 5, Figure 5.3 for diagram). Eye movements were not recorded in this experiment.

3.2.2.3 Design of the experiment

The experiment was a forced choice repeated measures design, subjects were asked to indicate the position of the target (right or left) when it disappeared from the centre of the screen using a joystick. If they did not see the target then they were instructed to guess the direction. The independent variable was the state of the shutters, i.e. all shutters open, LCP shutter closed or metal shutter closed. The dependent variables were the number of correct responses for rightward or leftward target presentations.

3.2.2.4 Procedure

The subject was positioned, using a chin and cheek rest, with the eyes 114cm in front of the translucent screen, with both eyes open. LCP shutters mounted on a headband were positioned in front of each eye. These were operated at 80Hz and run in phase with the LCP shutter positioned within the projector. The 1° target was presented centrally for 2.3s and then jumped randomly 5° to the right or 5° to the left for 200ms and then returned to the centre. This target presentation cycle was repeated 20 times in a 50s run. Eight runs for each subject were performed, giving a total of 160 target presentation cycles, with equal presentations made to the right or left. A 20s break was given between each run giving a total time of 9 minutes to complete all 160 presentations.

A programme operating all the shutters was run to create three stimulus conditions; all shutters open (i.e. left/right target visible), metal shutter closed in front of the target projector (i.e. left/right target invisible) and LCP shutter closed in front of the target projector (i.e. left/right target invisible on the screen if dissociation method effective).

The subject was instructed to look at the central target at all times and to indicate the perceived direction of the target by moving a joystick to the right or to the left when the central target disappeared. If the target was not seen to either side the subject was instructed to guess the direction.

The randomised target positions and shutter sequences are shown in Appendix 4. Of the 160 target presentations made, 24 were with all shutters open, 96 were with the LCP shutters closed and 40 were with the metal shutters closed.

3.2.3 Results

Table 3.4 and Figure 3.7 show the percentage of correct responses for each subject in each of the shutter conditions. Results from each subject were similar therefore the data was pooled. Figure 3.8 shows the pooled data for the group of five subjects. The mean number of correct responses for the group was 96.7% in the no shutter condition. The mean percentage of correct responses with the metal shutter was 46% and with the LCP shutter was 50.6%, where a 50% result would indicate guessing. A paired t-test confirmed that there was no significant difference between the responses with the metal shutter and the LCP shutter (target right and left: $t = -0.992$, $df = 4$, $p>0.05$, target right: $t = -0.757$, $df = 4$, $p>0.05$, target left: $t = -0.210$, $df = 4$, $p>0.05$). T-test details are shown in Appendix 3.4. When considering target presentations to the right and left, the number of correct responses was similar (see Table 3.4b & c and Figure 3.7b & c).

a)

Percentage of Correct Responses - (Right &Left)			
subject	**metal shutter**	**LCP shutter**	**no shutter**
1	42.5	49.0	91. 7
2	62.5	54.2	100.0
3	47.5	50.0	95.8
4	32.5	53.1	100.0
5	45.0	46.9	95.8
Mean	**46.0**	**50.6**	**96. 7**
SD	**10.8**	**3.0**	**3.5**
SE	**4.9**	**1.3**	**1. 6**

b)

Percentage of Correct Responses - (Right)			
subject	**metal shutter**	**LCP shutter**	**no shutter**
1	50.0	53.2	84.6
2	75.0	59.6	100.0
3	35.0	63.8	100.0
4	35.0	72.3	100.0
5	60.0	46.8	92.3
Mean	**51.0**	**59.2**	**95.4**
SD	**17.1**	**9.8**	**6.9**
SE	**7.7**	**4.4**	**3.1**

c)

Percentage of Correct Responses - (Left)			
subject	**metal shutter**	**LCP shutter**	**no shutter**
1	35.0	44.9	100.0
2	50.0	49.0	100.0
3	60.0	36.7	90.9
4	30.0	34.7	100.0
5	30.0	46.9	100.0
Mean	**41.0**	**42. 5**	**98.2**
SD	**13.4**	**6.4**	**4.1**
SE	**6.0**	**2.8**	**1.8**

Table 3.4: Percentage of correct responses for each subject in each shutter condition, a) all target presentations (right and left of centre), b) target presented to the right of centre, c) target presentations to the left of centre.

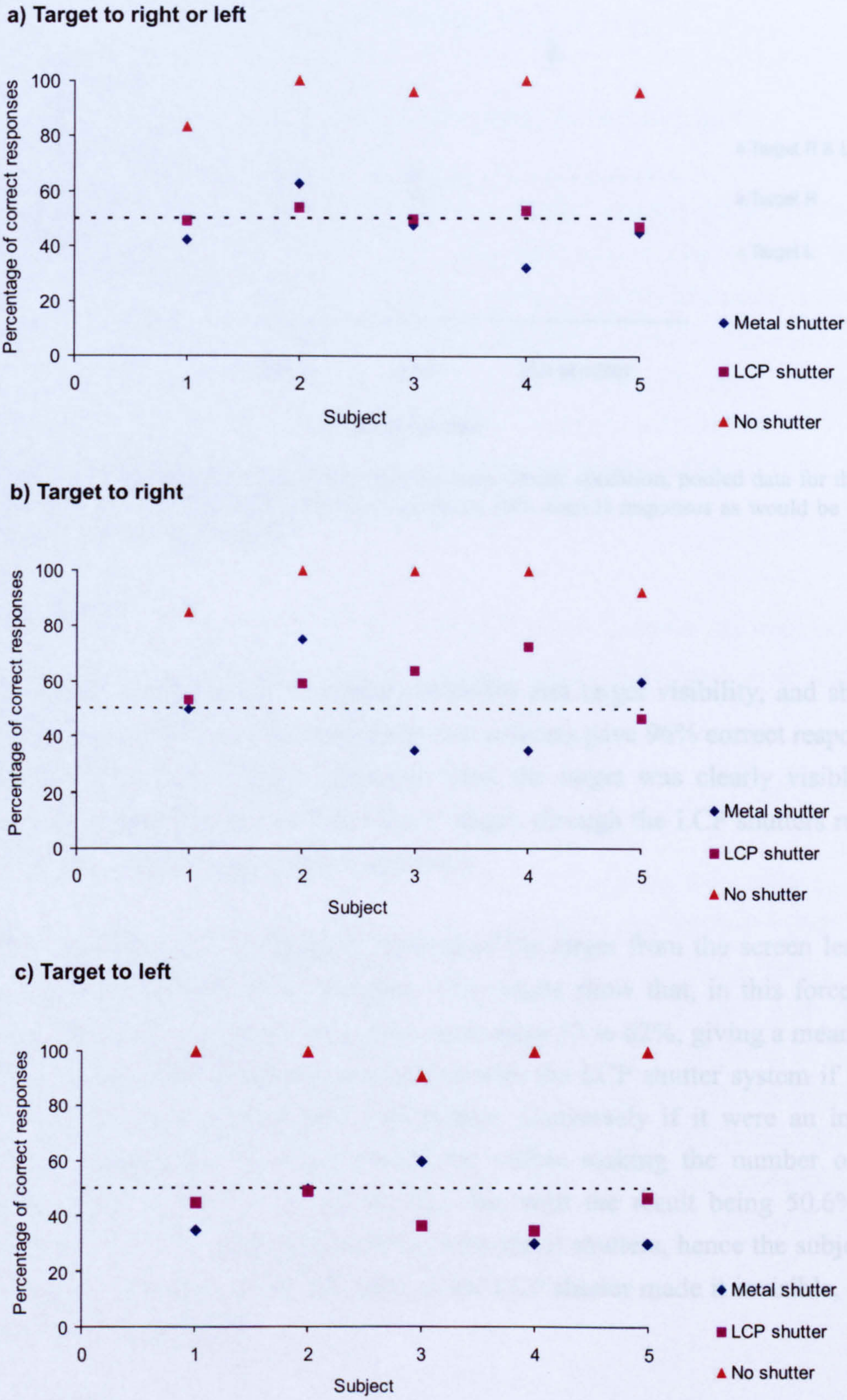


Figure 3.7: Percentage of correct responses for each subject in each shutter condition, a) all target presentations (right and left of centre), b) target presented to the right of centre, c) target presentations to the left of centre. Dotted line represents 50% correct responses as would be the case in guessing due to target being invisible.

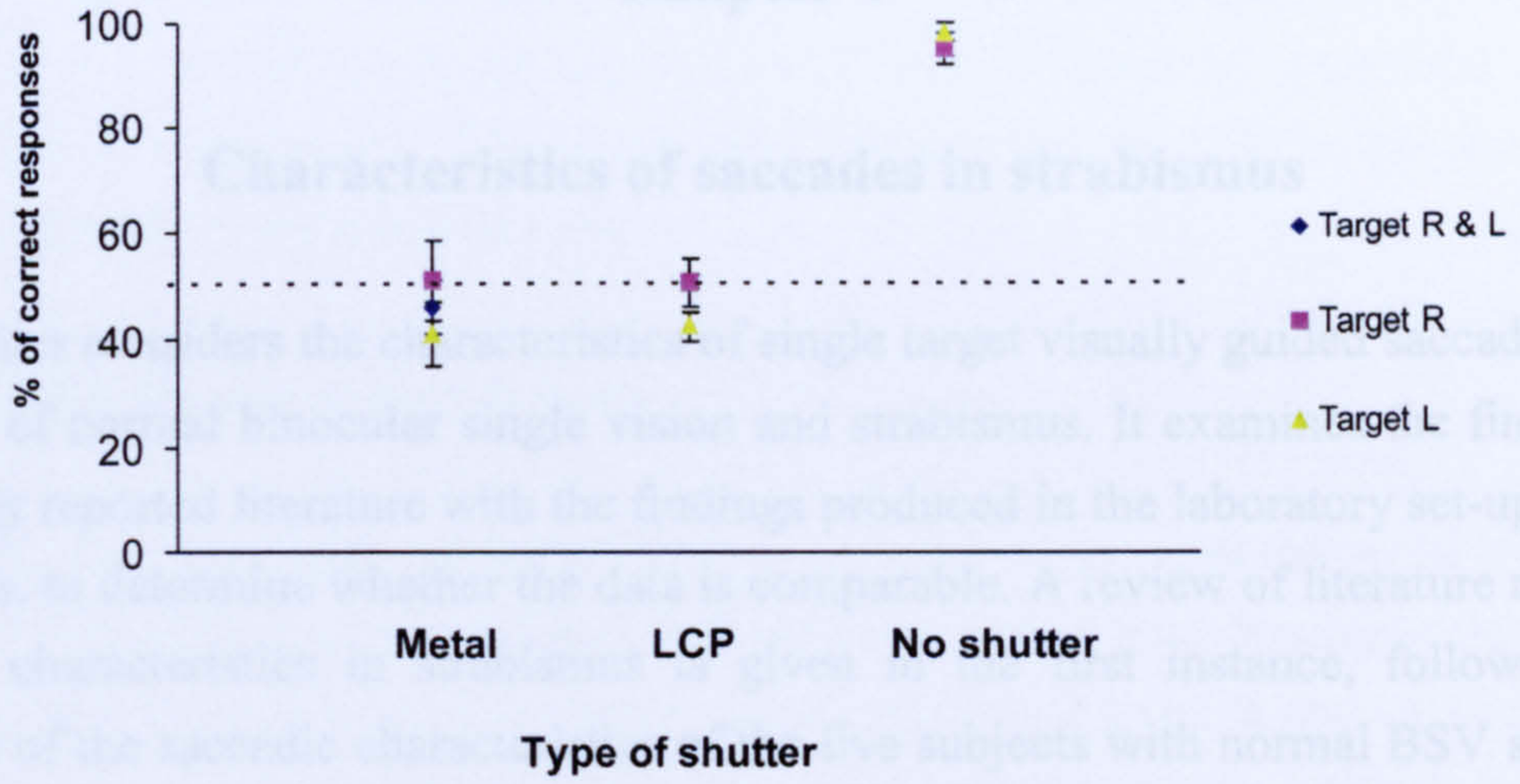


Figure 3.8: The percentage of correct responses for each shutter condition, pooled data for the group of five subjects. Error bars = ±1SE, dotted line represents 50% correct responses as would be the case in guessing due to target being invisible.

3.2.4 Discussion

The no shutter condition tested subject reliability and target visibility, and shows that two subjects gave 100% correct responses, two subjects gave 96% correct responses and one subject gave 92% correct responses when the target was clearly visible on the screen. This suggests good visibility of a 1° target, through the LCP shutters running at 80Hz and also suggests high subject sensitivity.

The metal shutter provides absolute removal of the target from the screen leading the subject to make a guess of the direction. The results show that, in this forced choice situation, the number of correct responses range from 32 to 62%, giving a mean of 46%. A similar result would therefore be expected with the LCP shutter system if it were a suitable method of providing total dissociation. Conversely if it were an ineffective method of dissociation, the target would be visible making the number of correct responses closer to 100%. It can be seen that with the result being 50.6% correct responses, the LCP shutters closely matched the metal shutters, hence the subjects were forced to guess the direction of the target as the LCP shutter made it invisible, therefore the hypothesis is supported.

3.2.5 Conclusion

The LCP shutter renders the target effectively invisible to visually normal subjects and therefore provides a suitable tool for dissociation of the eyes for use in experiments investigating binocular function, suppression and abnormal retinal correspondence.

Chapter 4

Characteristics of saccades in strabismus

This chapter considers the characteristics of single target visually guided saccades in the presence of normal binocular single vision and strabismus. It examines the findings of previously reported literature with the findings produced in the laboratory set-up used in this thesis, to determine whether the data is comparable. A review of literature reporting saccadic characteristics in strabismus is given in the first instance, followed by a summary of the saccadic characteristics of the five subjects with normal BSV and eight strabismic subjects who were included in the experiments of Chapters 5 and 6.

4.1 Introduction

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.

4.1.1 Saccade latency in strabismus

Stark, Ciuffreda and Kenyon (1981) 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 eleven subjects with amblyopia, with or without strabismus had saccade latency increased in the affected eye compared to the normal 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. They suggest therefore that it is amblyopia and not strabismus that affects saccade latency. Their study did not however report the characteristics of constant strabismus without amblyopia.

4.1.2 Saccade accuracy in strabismus

The accuracy of saccades in the dominant eye of strabismic subjects has been found to be comparable to binocular subjects. Van Leeuwen, de Faber, van der Steen and Collewijn (1995) studied the saccades of ten adult subjects with constant strabismus, two esotropic and eight 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. They concluded that saccades seem to be generated based on visual input from the dominant eye.

4.1.3 Saccade velocity in strabismus

De Faber, van Rijn and Collewijn (1994) compared saccades of eight strabismic subjects with amblyopia, one esotropic and seven exotropic, with five binocular controls using scleral coil recordings. The control group was found to have abducting saccades, which were greater in amplitude than adducting saccades, and peak velocity of the abducting eye was, on average, $12°s^{-1}$ higher than the adducting eye. In the strabismic group abducting saccades were 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 60° stimulus amplitude.

In contrast to the above study, Tian (1995) demonstrated no clear difference in peak velocity of saccades between binocular control subjects and strabismic subjects with constant exotropia.

4.1.4 Conjugacy of saccades in strabismus

De Faber, van Rijn and Collewijn (1994) compared saccades of eight strabismic subjects with amblyopia, one esotropic and seven exotropic, with five binocular controls using scleral induction coil recordings. The logMAR visual acuity in the amblyopic eye ranged from 0.1 to 1.0. The control group was found to have abducting saccades, which were greater in amplitude than adducting saccades, however the difference was <1°. In the strabismic group saccades towards the dominant eye were larger in the dominant eye with >1° difference between the two eyes. For 60° stimulus amplitude the mean difference in saccade size 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 60° stimulus amplitude the mean difference in saccade size 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, Bucci, Eggert and Garraud (1997) examined conjugacy of saccades measured using a Skalar infrared system in non-strabismic subjects, esotropes with deviations <10Δ and esotropes of >18Δ. The results are summarised in Table 4.1. Increased disconjugacy in strabismus was attributed to weakness or absence of disconjugate adaptive mechanisms. The increase of disconjugacy in subjects with larger strabismus supports the idea of more severely deficient adaptive mechanisms due to the total lack of binocular interaction, compared to 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. It seems, therefore, that binocular vision is important in maintaining binocular oculomotor coordination.

Group	Mean Disconjugacy
Non-strabismic (3 subjects)	0.5° divergent
Esotropia <10Δ (3 subjects)	1° variable - divergent / convergent
Esotropia >18Δ (4 subjects)	1.8° divergent

Table 4.1: Data of saccade disconjugacy from Kapoula et al (1997).

In contrast to the study by de Faber, van Rijn and Collewijn (1994), who reported larger and more consistently divergent disconjugacy when the non-amblyopic, non-strabismic eye abducted, Kapoula, Bucci, Eggert and Garraud (1997) found no directional specificity in the seven esotropic subjects. Maxwell, Lemij and Collewijn (1995) studied conjugacy of saccades in strabismus with deep amblyopia in ten subjects with esotropia and one with exotropia. They reported large amounts of disconjugacy, but did not show directional differences. The group studied by de Faber, van Rijn and Collewijn (1994) were mainly exotropes, suggesting a possible difference in the behaviour of esotropes and exotropes.

Three reasons for the small divergent disconjugacy typically found in normal binocular subjects have been suggested: Kapoula, Hain, Zee and Robinson (1987) suggested that the high-burst of saccadic pulse activity leads to disconnection of tonic vergence, thereby increasing divergence during a saccade. Zee, Fitzgibbon and Optican (1992) 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 co-exist, studies have not been conclusive regarding whether it is the presence of amblyopia or strabismus that leads to disconjugacy. Maxwell, Lemij and Collewijn (1995) studied subjects with strabismus and deep amblyopia, ten with count fingers (CF) vision and one with 6/60 in the amblyopic eye. They demonstrated disconjugate saccades in all subjects, but significantly larger disconjugacy in the subjects with CF vision compared to 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, Bucci, Eggert and Garraud (1997) found similar amounts of disconjugacy in esotropia without amblyopia suggesting that strabismus alone is sufficient to disrupt saccade conjugacy. Kapoula, Bucci, Eggert and Garraud (1997) suggest that the disconjugacy may exist in strabismus without amblyopia due to a weakness or absence of disconjugate adaptive mechanisms (see Chapter 7 for further discussion).

Despite the reported disconjugacy of saccades in strabismus it is apparent that the disconjugacy is a consistent finding and the strabismic eye does not aimlessly wander as might be anticipated in unilateral blindness. 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.

4.1.5 Saccades in alternating strabismus

Van Leeuwen, de Faber, van der Steen and Collewijn (1999) studied horizontal saccades in six alternating exotropes using the scleral coil technique. These subjects were found to alternate the viewing eye during saccades in some circumstances. For large symmetric 40° target stimuli they made accurate saccades in which they fixated targets to the left with the left eye and targets to the right with the right eye. Smaller and eccentric target stimuli produced differences in behaviour between subjects. The authors proposed that the finding of saccades, which start with one eye and end with the other, suggest that in alternating strabismus saccade programming is based on one eye only, and alternates between eyes.

4.2 Experiment 3: Documentation of saccade characteristics in strabismus

The following saccadic eye movement data was collected from subjects with normal BSV and subjects with strabismus, following a clinical examination and prior to the distractor experiments presented in Chapters 5 and 6. The purpose of this was threefold:

1. To familiarise subjects, who had not previously carried out eye movement experiments, with the equipment, target presentation and task of proposed later experiments.
2. To ensure that any subjects recruited for experiments were reliable, in terms of remaining stationary, giving few blinks and generally tolerant to the laboratory conditions.
3. To characterise any differences in certain saccadic parameters between subjects with normal BSV and those with strabismus.

4.2.1 Hypotheses

For saccades made to a target presented to both eyes:

1. There will be no difference in saccade latency of the dominant eye in binocular subjects and subjects with strabismus.
2. There will be no difference in saccade gain of the dominant eye in binocular subjects and subjects with strabismus.
3. Saccades will be more disconjugate in strabismic subjects than binocular subjects.

4.3 Method

4.3.1 Participants

Five subjects with normal corrected visual acuity, bifoveal binocular single vision and stereoacuity of at least 60" of arc using the TNO test, were included. The mean age of the participants was 20.6 years (range 19.0 - 21.8 years). Eight subjects with constant strabismus, three with exotropia and five with esotropia, were also studied.

All eight subjects with constant manifest strabismus underwent a clinical examination. The type and size of deviation was confirmed using the cover test and prism cover test respectively, at 0.33m, 1.14m and 6m. All subjects were assessed for anomalous BSV

or potential normal BSV with their angle corrected with both prisms in free space and with the synoptophore. The type of retinal correspondence, normal or abnormal, was determined in each case. In those with suppression, confirmed with Worth's lights, Bagolini glasses and the polarised four-dot test, the area and density of suppression were measured. In those with abnormal BSV confirmed by Bagolini glasses, sensory fusion was further investigated using more dissociative tests (polarised 4-dot test and Worth's lights). Anomalous motor fusion (prism fusion range and synoptophore) and stereoacuity (Frisby, Lang and TNO) were also assessed. Full clinical results of these investigative tests are shown in Appendix 5 (subjects 1-8).

Six of the subjects had suppression with no demonstrable BSV and two subjects with esotropia had ARC and anomalous BSV, Table 4.2 summarises the subject details. The mean age of the strabismic subjects was 30.6 years (range 18.1 - 62.8years). None of the subjects had previous experience of eye movement recording equipment.

Subj	Age (years)	VA		Strabismus	PCT at 1.14m (Δ)	Retinal corresp.	Suppression	Abnormal BSV		
		RE	LE					Sensory fusion	Motor fusion	SV
1	62.8	6/5	6/12	LXT	2 BI	NRC	yes	no	no	no
2	22.8	6/6	6/4	RET	6 BO	NRC	yes	no	no	no
3	20.2	6/6	6/4	RET	6 BO	NRC	yes	no	no	no
4	41.0	6/4	6/6	LXT	12 BI	NRC	yes	no	no	no
5	39.5	6/24	6/5	RET	12 BO	NRC	yes	no	no	no
6	19.4	6/5	6/9	LXT	18 BI	NRC	yes	no	no	no
7	20.9	6/4	6/6	LET	12 BO	ARC	no	yes	yes	gross
8	18.1	6/5	6/6	LET	10 BO	ARC	no	yes	yes	200"

Table 4.2: Summary of clinical details of strabismic subjects. XT = exotropia, ET = esotropia, L/R denotes left or right eye, NRC = normal retinal correspondence, ARC = abnormal retinal correspondence, PCT = prism cover test, SV = stereoscopic vision. Stereoscopic vision was demonstrated using the gross synoptophore slides in subject 7 and 200 seconds of arc on the Lang stereotest in subject 8.

4.3.2 Apparatus and stimuli

The laboratory was set-up as described in Chapter 2. Eye movements were recorded using the Skalar infrared limbal tracker, head movements were restricted by use of chin and cheek rests. The eye movement data was stored on disk and analysed off-line.

A 1° cross (shown in Figure 4.1) was presented by back projection from a modified Kodak carousel slide projector in the centre of the flat translucent screen 114cm from the subject. A mirror galvanometer sited in front of the projector was used to move the

target randomly to either +4° or +8° eccentricities along the horizontal axis. The target was visible to both eyes at all times.

Figure 4.1: 1° target cross

4.3.3 Procedure

The subjects were seated in a comfortable office chair with the Skalar infrared eye movement recorder and LCP shutters clamped in position. Pursuit eye movements, generated using a sinusoidal target motion of 0.32Hz of amplitude ±12°, were used to calibrate the eye movement recorder before each trial, as described in Section 2.1.

The subjects were informed that all targets would initially appear in the centre of the screen and always move to the right and then back to the centre. This direction was maintained for all subsequent trials as planned for later distractor experiments. The target was presented centrally and, to avoid anticipation, there was a random period (500 - 1200ms) before the target disappeared and immediately reappeared at either 4° or 8° on the horizontal axis for 500ms (nominally zero gap). The target then returned to the centre point before the next trial. A total of 60 trials were run for each subject, taking a total time of approximately 5 minutes.

The subjects were instructed to look directly at the centre of the small target cross, positioned in the middle of the screen and, when it jumped to the right, to move their eyes as quickly and accurately as possible to continue looking at the centre of the cross. They were told not to anticipate the target movement and that they should only move their eyes when they saw it appear.

4.4 Results

Data was collected and analysed for all thirteen subjects. The co-operation of all subjects was good. The mean number of saccades rejected due to blinks, loss of fixation

or incorrect saccade direction, was 12% (range 5% - 18%) in the BSV group and 15% (range 10% - 22%) in the strabismic group,

4.4.1 Saccade Latency

Tables 4.3 and 4.4 show saccade latency of the dominant eye for each saccade direction and saccade amplitude for the BSV group and the strabismic group respectively. Figure 4.2 shows the mean group data. This shows that saccade latency was similar for both amplitudes and that the strabismic subjects had slightly longer saccade latencies than the subjects with BSV.

Subject	Rightward saccades		Leftward saccades	
	4° target	8° target	4° target	8° target
1	149.6 SD 15.1	140.4 SD 24.1	138.2 SD 15.1	132.6 SD 20.2
2	138.1 SD 19.8	139.4 SD 19.7	139.4 SD 14.5	143.1 SD 22.0
3	148.4 SD 18.8	147.1 SD 14.1	146.0 SD 15.1	139.9 SD 17.9
4	174.5 SD 19.1	178.5 SD 22.5	173.1 SD 17.2	177.1 SD 18.5
5	152.9 SD 13.7	149.3 SD 19.5	150.8 SD 15.5	149.5 SD 16.3
Mean	**152.7**	**150.9**	**149.5**	**148.4**
SD	**13.4**	**16.0**	**14.1**	**17.1**
SE	**6.0**	**7.1**	**6.3**	**7.7**

Table 4.3: Mean saccade latency (ms) of five subjects with normal BSV. Latencies of the dominant eye are presented. SD = standard deviation, SE = standard error.

To determine whether there was any difference in saccade latency for the BSV group, for the two amplitudes and directions, a two-factor repeated measures ANOVA was performed. There was no significant difference in saccade latency for different amplitudes [$F(1,4)=0.458$, $p>0.05$] or direction [$F(1,4)=1.941$, $p>0.05$]. (ANOVA details in Appendix 6.1). Similarly for saccade latency in the strabismic group, for the two amplitudes and directions, a two-factor repeated measures ANOVA was performed. There was no significant difference in saccade latency for different amplitudes [$F(1,7)=4.529$, $p>0.05$] or directions [$F(1,7)=0.757$, $p>0.05$]. The data for each direction and amplitude was therefore combined for each subject. Pooled data for each group is shown in Table 4.5. (ANOVA details in Appendix 6.2).

Subject	Rightward saccades		Leftward saccades	
	4° target	8° target	4° target	8° target
1	185.1 SD 20.1	180.9 SD 25.1	184.6 SD 26.7	186.4 SD 28.8
2	159.6 SD 20.0	160.6 SD 20.4	164.9 SD 19.1	167.1 SD 22.4
3	140.8 SD 17.2	149.2 SD 19.3	145.5 SD 19.4	145.9 SD 19.6
4	159.9 SD 15.3	163.9 SD 17.7	155.6 SD 14.8	160.1 SD 18.7
5	164.3 SD 14.4	167.5 SD 19.6	165.3 SD 15.6	166.2 SD 20.7
6	160.7 SD 20.0	163.4 SD 19.2	158.5 SD 12.3	154.8 SD 20.2
7	164.1 SD 19.9	166.7 SD 15.5	160.7 SD 18.4	162.4 SD 17.6
8	138.7 SD 17.2	136.5 SD 17.4	130.6 SD 18.1	132.5 SD 18.8
Mean	**159.2**	**161.1**	**158.2**	**159.4**
SD	**14.6**	**13.2**	**15.7**	**15.9**
SE	**5.1**	**4.7**	**5.6**	**5.6**

Table 4.4: Mean saccade latency (ms) of individual subjects with constant strabismus. Latencies of the fixing eye presented. SD = standard deviation, SE = standard error.

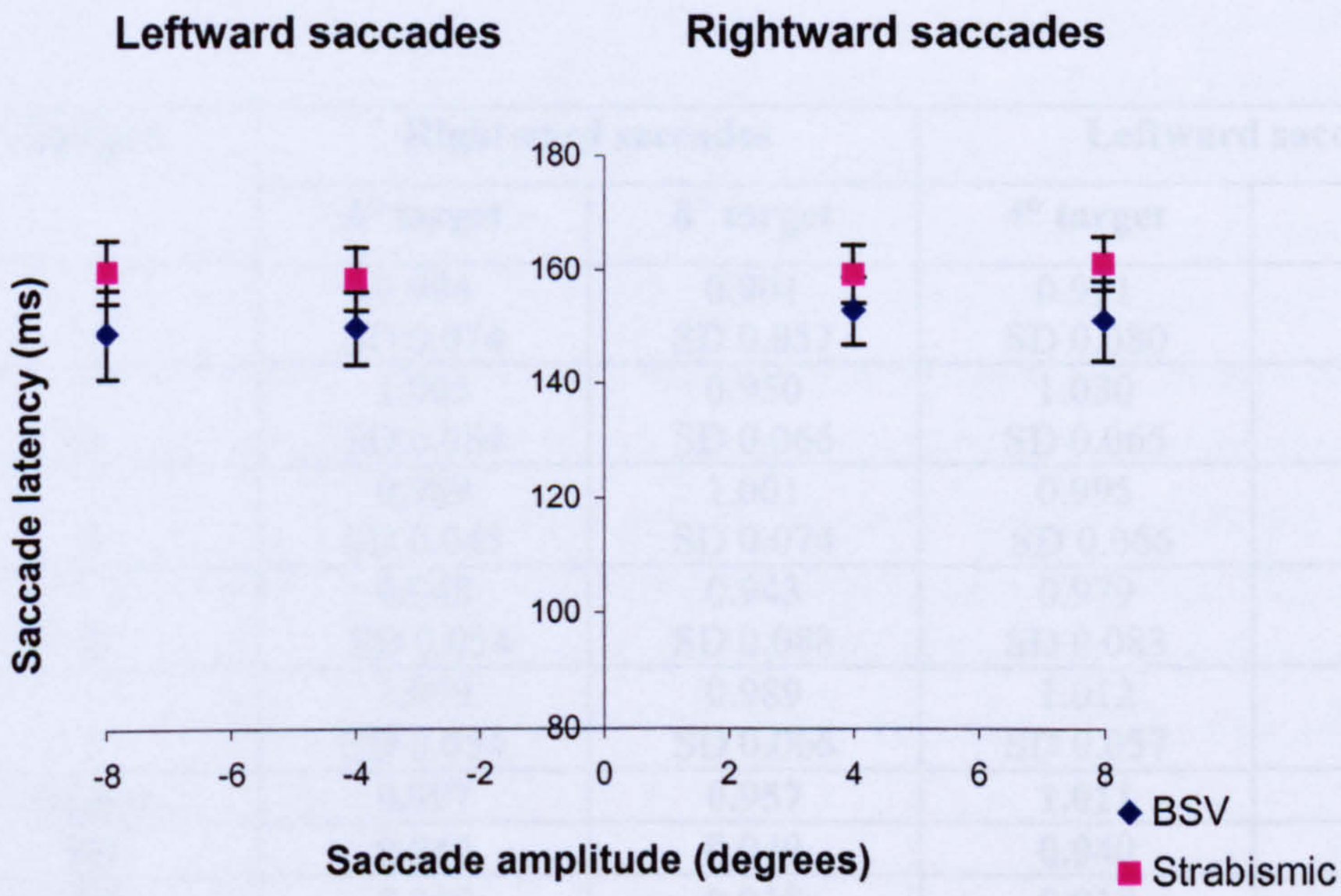


Figure 4.2: Mean saccade latency for each group plotted against target amplitude.

Table 4.5 shows that the strabismic subjects had slightly larger saccade latency compared to the BSV group (9.1ms) however this was not found to be significantly different supporting hypothesis 1 (unpaired t-test, t = -1.081, df = 11, p>0.05). Appendix 6.3 gives full details of statistical tests used.

Group	BSV	Strabismus
Mean	150.4	159.5
SD	14.9	14.7
SE	6.6	5.2

Table 4.5: Mean saccade latency (ms) for all saccade amplitudes and directions, pooled data for each subject group. SD = standard deviation, SE = standard error.

4.4.2 Saccade gain

Table 4.6 shows the mean saccade gain for each subject in the BSV group and Table 4.7 shows the strabismic group data. Figure 4.3 shows the group mean saccade gain plotted against amplitude. This shows that saccades to 4° targets were extremely accurate and saccades to 8° targets were slightly hypometric.

Subject	Rightward saccades		Leftward saccades	
	4° target	8° target	4° target	8° target
1	0.984 SD 0.074	0.901 SD 0.057	0.991 SD 0.080	0.904 SD 0.067
2	1.005 SD 0.084	0.950 SD 0.066	1.080 SD 0.065	0.918 SD 0.072
3	0.989 SD 0.045	1.001 SD 0.074	0.995 SD 0.066	0.946 SD 0.076
4	0.948 SD 0.054	0.943 SD 0.088	0.979 SD 0.083	0.967 SD 0.104
5	1.059 SD 0.054	0.989 SD 0.066	1.012 SD 0.057	0.969 SD 0.073
Mean	**0.997**	**0.957**	**1.011**	**0.941**
SD	**0.040**	**0.040**	**0.040**	**0.029**
SE	**0.018**	**0.018**	**0.018**	**0.013**

Table 4.6: Mean saccade gain of five subjects with BSV. SD = standard deviation, SE = standard error.

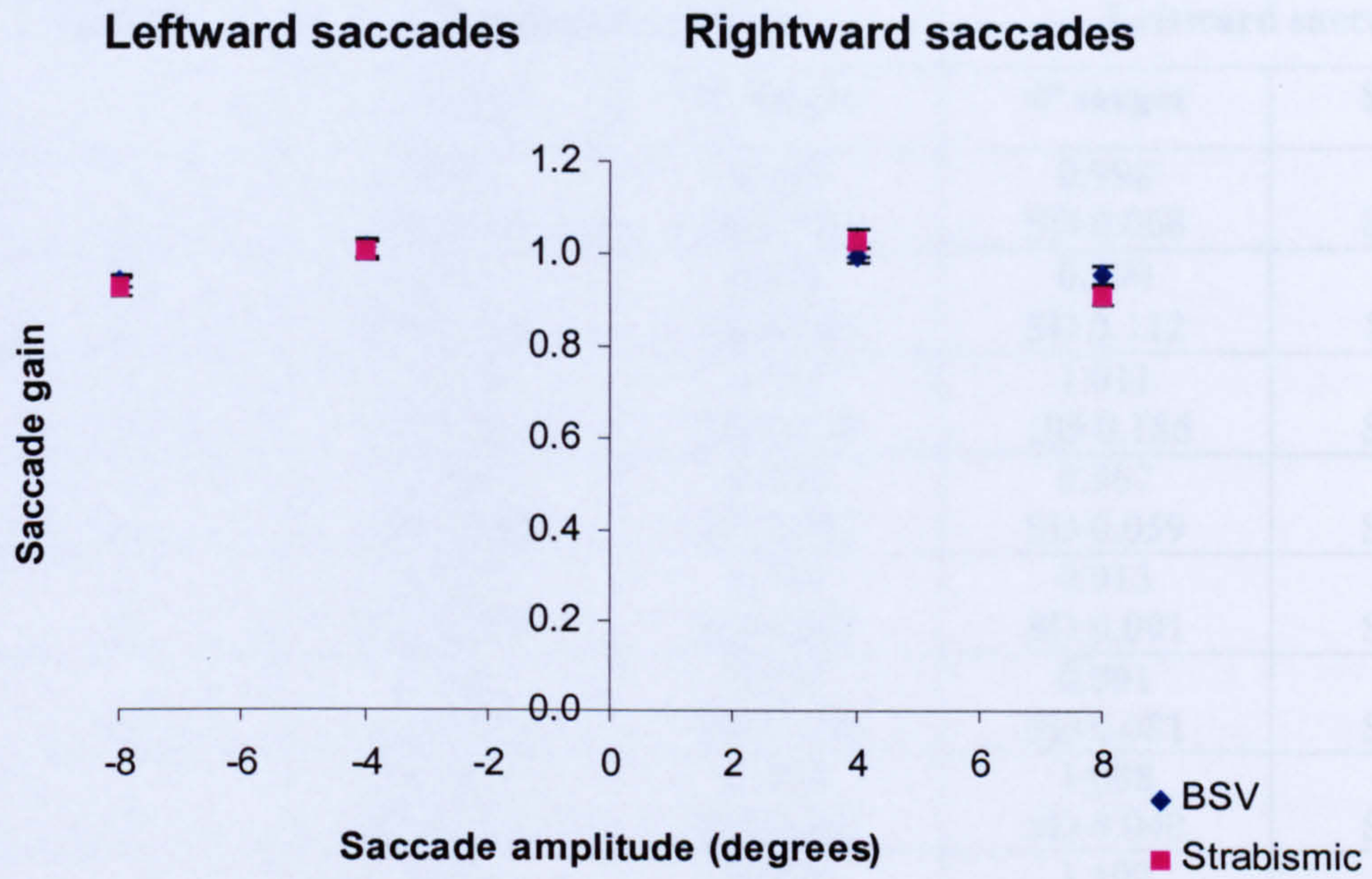


Figure 4.3: Saccade gain in BSV and strabismic subjects.

To determine whether there was any significant difference in saccade gain for the BSV group, for the two amplitudes and directions, a two-factor repeated measures ANOVA was performed (ANOVA details in Appendix 6.4). There was a significant difference in saccade gain for different amplitudes [$F(1,7)=8.457$, $p<0.05$] showing that the gain to 8° targets was significantly less than 4° targets. There was no significant difference in gain between saccades to the right and left [$F(1,7)=0.0001$, $p>0.05$]. Similarly for saccade gain in the strabismic group, for the two amplitudes and directions, a two-factor repeated measures ANOVA was performed (ANOVA details in Appendix 6.5). As for the BSV group there was a significant difference in saccade gain for different amplitudes [$F(1,7)=28.290$, $p<0.01$] showing that the gain to 8° targets was less than to 4° targets. There was no significant difference in gain between saccades to the right and left, [$F(1,7)=0.757$, $p>0.05$]. The gain of saccades made towards the fixing eye or strabismic eye was also compared using a two-factor ANOVA and no significant difference was found [$F(1,7)=0.916$, $p>0.05$] (ANOVA details in Appendix 6.6). The data for each direction was therefore combined for each subject. Pooled data for each group is shown in Table 4.8.

Subject	Rightward saccades		Leftward saccades	
	4° target	8° target	4° target	8° target
1	0.982 SD 0.075	0.896 SD 0.081	0.998 SD 0.068	0.989 SD 0.078
2	0.966 SD 0.133	0.929 SD 0.140	0.990 SD 0.112	0.974 SD 0.111
3	1.198 SD 0.205	0.958 SD 0.178	1.011 SD 0.186	0.861 SD 0.209
4	0.986 SD 0.080	0.904 SD 0.097	0.967 SD 0.059	0.878 SD 0.095
5	0.927 SD 0.098	0.810 SD 0.087	0.913 SD 0.091	0.858 SD 0.083
6	1.055 SD 0.084	0.924 SD 0.108	0.991 SD 0.081	0.939 SD 0.118
7	1.086 SD 0.045	0.988 SD 0.055	1.088 SD 0.040	0.962 SD 0.059
8	1.003 SD 0.097	0.899 SD 0.088	1.107 SD 0.075	0.980 SD 0.083
Mean	**1.025**	**0.914**	**1.008**	**0.930**
SD	**0.086**	**0.052**	**0.063**	**0.056**
SE	**0.030**	**0.019**	**0.022**	**0.020**

Table 4.7: Mean saccade gain of eight subjects with strabismus. SD = standard deviation, SE = standard error.

Table 4.8 shows that both BSV and strabismic subjects had accurate saccades to 4° targets with a mean gain of 1.0, however the strabismic group had less accurate saccades compared to the BSV group for 8° targets. This difference was not found to be significantly different supporting hypothesis 2 (unpaired t-test, t=-1.178, df = 11, $p>0.05$). T test details are shown in Appendix 6.7.

Group	BSV		Strabismus	
	4° target	8° target	4° target	8° target
Mean	1.004	0.949	1.017	0.922
SD	0.034	0.031	0.063	0.044
SE	0.015	0.014	0.022	0.015

Table 4.8: Mean saccade gain for both saccade directions, pooled data for each subject group.

4.4.3 Binocular co-ordination of saccades

The amplitude of the right eye was subtracted from the amplitude of the left eye to give a measure of saccade disconjugacy in degrees. Table 4.9 shows the mean saccade disconjugacy for each subject in the BSV group and Tables 4.10 and 4.11 show the group data for esotropes and exotropes respectively. Positive values indicate convergent disconjugacy and negative values divergent disconjugacy. Figure 4.4 shows individual subjects disconjugacy for 8° targets. Figure 4.5 shows typical saccade disconjugacy of subjects with BSV and strabismus.

Table 4.9 shows that four of the BSV subjects demonstrated a small divergent disconjugacy and one subject had a minimal convergent disconjugacy for saccades of both amplitudes and directions. The three subjects with left exotropia also had divergent disconjugacy for saccades of both amplitudes and directions, but this was approximately three times the size of the BSV subjects. The five subjects with esotropia had inconsistent disconjugacy. Subjects 5 and 8 had convergent disconjugacy for both amplitudes and direction. Subjects 3 and 7 had convergent disconjugacy for leftward saccades and divergent disconjugacy for rightward saccades, whilst subject 2 had the opposite of this. Table 4.12 shows disconjugacy in the esotropic subjects for saccades towards the fixing eye or the strabismic eye. This demonstrates that when saccades are made towards the strabismic eye disconjugacy becomes increasingly convergent. This is true for all subjects with the exception of subject 3.

To test for any significant difference in saccade disconjugacy in the BSV group, for the two amplitudes and directions, a two-factor repeated measures ANOVA was performed (ANOVA details in Appendix 6.8). There was a significant difference in saccade disconjugacy for different amplitudes [$F(1,4)=17.963$, $p<0.05$] showing that the disconjugacy to 8° targets was significantly more than 4° targets. There was no significant difference between saccades to the right and left [$F(1,4)=0.010$, $p>0.05$]. Similarly for saccade disconjugacy in the strabismic group, for the two amplitudes and directions, a two-factor repeated measures ANOVA was performed for esotropes and exotropes (ANOVA details in Appendices 6.9 and 6.10). In both types of strabismus there was a significant difference in saccade disconjugacy for different amplitudes [esotropia: $F(1,4)=14.593$, $p<0.05$, exotropia: $F(1,2)=18.879$, $p<0.05$] showing that the disconjugacy to 8° targets was slightly more than to 4° targets.

Subject	Rightward		Leftward	
	4°	8°	4°	8°
1	-0.24	-0.32	-0.28	-0.36
2	-0.08	-0.11	-0.10	-0.13
3	0.15	0.09	0.10	0.08
4	-0.18	-0.28	-0.10	-0.22
5	-0.30	-0.39	-0.33	-0.34
Mean	**-0.13**	**-0.20**	**-0.14**	**-0.19**
SD	**0.18**	**0.19**	**0.17**	**0.18**

Table 4.9: Saccade disconjugacy in five subjects with normal BSV. Positive values represent convergent disconjugacy and negative values represent divergent disconjugacy. SD = standard deviation.

Subject	Rightward		Leftward	
	4°	8°	4°	8°
2	0.76	1.93	-0.52	-1.29
3	-1.23	-1.51	0.48	0.94
5	0.52	0.65	0.76	1.13
7	-0.55	-0.93	0.74	1.63
8	0.61	0.62	0.68	1.68
Mean	**0.02**	**0.15**	**0.43**	**0.82**
SD	**0.87**	**1.37**	**0.54**	**1.09**

Table 4.10: Saccade disconjugacy in five subjects with esotropia. Positive values represent convergent disconjugacy; negative values represent divergent disconjugacy. SD = standard deviation.

Subject	Rightward Saccades to fixing eye		Leftward Saccades to strabismic eye	
	4°	8°	4°	8°
1	-0.53	-0.44	-1.11	-1.84
4	-0.12	-0.65	-0.53	-1.38
6	-0.53	-0.86	-0.10	-0.62
Mean	**-0.39**	**-0.65**	**-0.58**	**-1.28**
SD	**0.24**	**0.21**	**0.51**	**0.62**

Table 4.11: Magnitude of saccade disconjugacy in degrees for three subjects with left exotropia. Negative values represent divergent disconjugacy. SD = standard deviation.

Subject	Saccades to fixing eye		Saccades to strabismic eye	
	4°	8°	4°	8°
2	-0.52	-1.29	0.76	1.93
3	0.48	0.94	-1.23	-1.51
5	0.52	0.65	0.76	1.13
7	-0.55	-0.93	0.74	1.63
8	0.61	0.62	0.68	1.68
Mean	**0.11**	**-0.002**	**0.34**	**0.97**
SD	**0.59**	**0.92**	**0.88**	**1.42**

Table 4.12: Magnitude of saccade disconjugacy (in degrees) for five subjects with esotropia for saccades towards the fixing eye and towards the strabismic eye. Positive values represent convergent disconjugacy; negative values represent divergent disconjugacy. SD = standard deviation.

There was no significant difference in disconjugacy for saccade direction, to the left or right, [esotropia: $F(1,4)=0.475$, $p>0.05$, exotropia: $F(1,2)=1.091$, $p>0.05$].

As all of the exotropes had left strabismus these results also indicate that, despite a trend for more divergent disconjugacy towards the strabismic eye, this was not statistically significant. The disconjugacy of saccades made towards the fixing eye or strabismic eye of the esotropic group was compared using a two-factor repeated measures ANOVA and no significant difference was found for direction [$F(1,4)=0.623$, $p>0.05$]. ANOVA details in Appendix 6.11.

From Tables 4.9 and 4.10 and Figure 4.3 it is evident that both exotropic and esotropic subjects showed larger disconjugacy than the subjects with BSV. To compare disconjugacy between the strabismic subjects and the binocular subjects unpaired t-tests were performed. For exotropic subjects there was no significant difference from BSV subjects in disconjugacy for 4° targets (saccades towards fixing eye: $t = 1.784$, $df = 6$, $p>0.05$, saccades towards strabismic eye: $t = 1.867$, $df = 6$, $p>0.05$). The difference was significantly different however for 8° targets (saccades towards fixing eye: $t = 3.163$, $df = 6$, $p<0.05$, saccades towards strabismic eye: $t = 3.824$, $df = 6$, $p<0.01$) showing that in exotropia disconjugacy was more divergent than in BSV subjects. Details of t-tests in Appendix 6.12. For the 5 esotropic subjects there was no significant difference from the BSV group for 4° targets, (saccades towards fixing eye: $t = -0.888$, $df = 8$, $p>0.05$, saccades towards strabismic eye: $t = -1.192$, $df = 8$, $p>0.05$), or for 8° targets (saccades towards the fixing eye: $t = -0.420$, $df = 8$, $p>0.05$, saccades towards strabismic eye: $t = -1.830$, $df = 8$, $p>0.05$). Details of t-tests in Appendix 6.13.

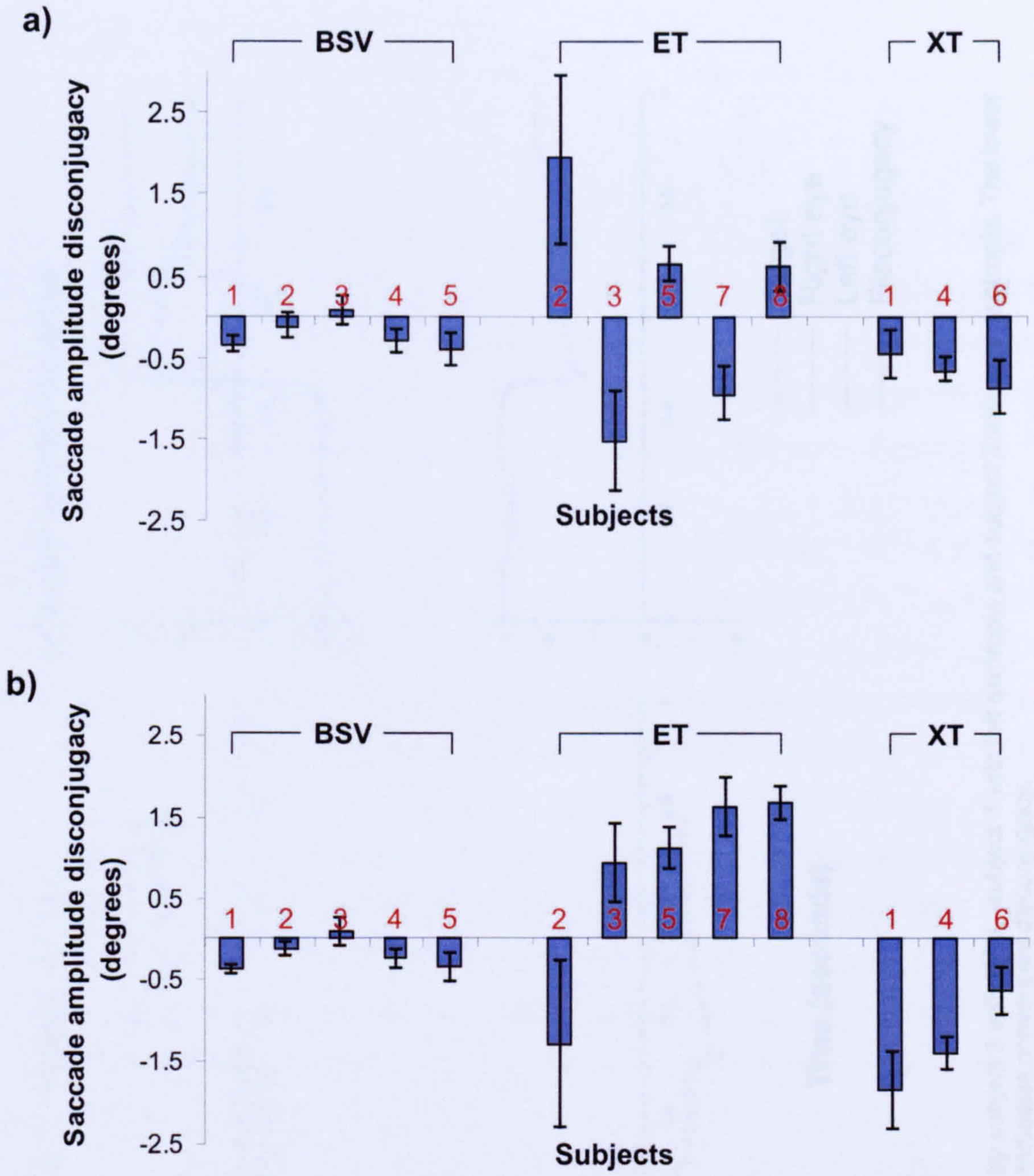


Figure 4.4: Mean saccade disconjugacy for 8° targets in each subject a) rightward saccades, b) leftward saccades. Error bar represent ±1SD. BSV indicates the results of the five subjects with normal BSV, ET indicates the results of the five subjects with esotropia and XT indicates the results of the three subjects with exotropia.

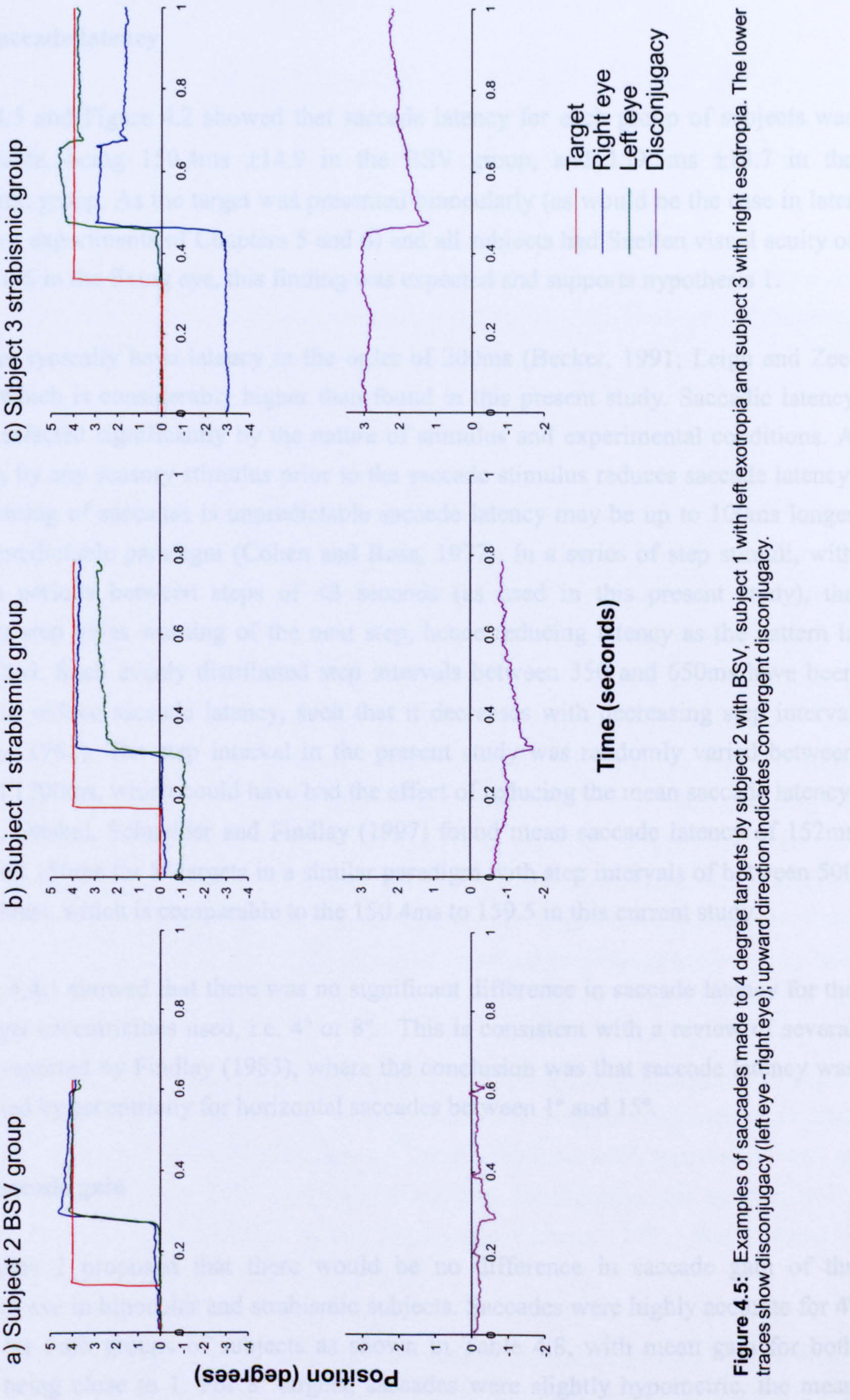


Figure 4.5: Examples of saccades made to 4 degree targets by subject 2 with BSV, subject 1 with left exotropia and subject 3 with right esotropia. The lower traces show disconjugacy (left eye - right eye); upward direction indicates convergent disconjugacy.

4.5 Discussion

4.5.1 Saccade latency

Table 4.5 and Figure 4.2 showed that saccade latency for each group of subjects was comparable, being 150.4ms ±14.9 in the BSV group, and 159.5ms ±14.7 in the strabismic group. As the target was presented binocularly (as would be the case in later distractor experiments of Chapters 5 and 6) and all subjects had Snellen visual acuity of at least 6/6 in the fixing eye, this finding was expected and supports hypothesis 1.

Saccades typically have latency in the order of 200ms (Becker, 1991; Leigh and Zee, 1999), which is considerably higher than found in this present study. Saccadic latency can be affected significantly by the nature of stimulus and experimental conditions. A warning by any sensory stimulus prior to the saccade stimulus reduces saccade latency. If the timing of saccades is unpredictable saccade latency may be up to 100ms longer than a predictable paradigm (Cohen and Ross, 1977). In a series of step stimuli, with fixation periods between steps of <3 seconds (as used in this present study), the previous step gives warning of the next step, hence reducing latency as the pattern is established. Such evenly distributed step intervals between 350 and 650ms have been shown to reduce saccade latency, such that it decreases with decreasing step interval (Findlay, 1981). The step interval in the present study was randomly varied between 500 and 1200ms, which could have had the effect of reducing the mean saccade latency. Walker, Deubel, Schneider and Findlay (1997) found mean saccade latency of 152ms for 4° and 156ms for 8° targets in a similar paradigm with step intervals of between 500 and 1000ms, which is comparable to the 150.4ms to 159.5 in this current study.

Section 4.4.1 showed that there was no significant difference in saccade latency for the two target eccentricities used, i.e. 4° or 8°. This is consistent with a review of several studies reported by Findlay (1983), where the conclusion was that saccade latency was unaffected by eccentricity for horizontal saccades between 1° and 15°.

4.5.2 Saccade gain

Hypothesis 2 proposed that there would be no difference in saccade gain of the dominant eye in binocular and strabismic subjects. Saccades were highly accurate for 4° targets for both groups of subjects as shown in Table 4.8, with mean gain for both groups being close to 1. For 8° targets, saccades were slightly hypometric, the mean

gain being 0.949 for the BSV group and 0.922 for the strabismic group, but this difference was not significant. The hypothesis was therefore supported.

The task, stimulus size and brightness and the background around the target all influence saccade accuracy. This decrease in accuracy for 8° targets was expected (Bartz, 1967; Becker, 1972) as the percentage of undershooting saccades increases, and overshooting saccades decreases, as the stimulus amplitude increases, (see Chapter 1, Figure 1.4). Kapoula and Robinson (1986) showed that the range of target positions used in an experimental session influences the accuracy of saccades, such that distances at the upper end of the range are underestimated, and those at the lower end of the range overestimated, regardless of the absolute amplitude.

4.5.3 Saccade disconjugacy

Figure 4.4 showed that saccade disconjugacy in the BSV group was divergent and <0.4° in all subjects, hence saccades of the abducting eye were slightly larger than the adducting eye. This compared to the mean divergent disconjugacy in the exotropic subjects of 0.7° with a range of -0.1° to -1.8° and a mean convergent disconjugacy in the esotropic subjects of 0.4° with a more varied range of -1.3° to +1.9°. Hypothesis 3 proposed that saccades would be more disconjugate in strabismic subjects than binocular subjects. In exotropic subjects this was supported for 8° targets (Appendix 6.12) but there was no statistical difference between BSV and esotropic subjects (Appendix 6.13). From Table 4.12 it is clear that all five esotropic subjects had disconjugacy greater than the BSV subjects but this did not reach statistical significance due to the variable convergent or divergent disparity seen between subjects. From Figure 4.3 highlights the increased disconjugacy in esotropic subjects compared to BSV subjects and supports hypothesis 3.

Of particular interest in the strabismic subjects is the finding, as demonstrated in Figure 4.4, that disconjugacy in the two subjects with clinically demonstrable anomalous BSV (subjects 7 and 8) was larger than four of the six subjects with suppression and no demonstrable BSV (normal or abnormal). This does not therefore add support to the proposed hypothesis of Kapoula, Bucci, Eggert and Garraud (1997) that absence of binocular vision is the cause of disconjugacy.

The results of this present study have demonstrated smaller disconjugacy than de Faber, van Rijn and Collewijn (1994). This is most likely due to the small amplitudes in the

present study, however, they are comparable with results for esotropes reported by Kapoula, Bucci, Eggert and Garraud (1997) shown in Table 4.1.

Tables 4.11 and 4.12 demonstrate that both esotropic and exotropic subjects had a tendency for disconjugacy to increase when saccades were made towards the fixing eye, becoming more convergent in esotropia and more divergent in exotropia. This was not statistically significant, but it is possible that this could become significant for larger amplitude saccades. This is in contrast to the findings of Kapoula, Bucci, Eggert and Garraud (1997) who found no directional differences and de Faber, van Rijn and Collewijn (1994) who reported that saccades were more conjugate towards the strabismic eye than towards the dominant eye.

4.5.4 Experimental design

As intended, the results do not provide a totally comprehensive characterisation of saccades in strabismus since the primary aim was to familiarise subjects with the equipment and stimuli to be used in the experiments of Chapters 5 and 6, using only 4° and 8° target eccentricities. It was established, however, that saccade latency and gain (parameters to be collected in later experiments) were equivalent in the two groups of subjects. This demonstrated that they were comparable to previously reported literature using similar forms of target presentation. Further extensive studies beyond the scope of this thesis, using monocular and binocular fixation, would be required to fully document saccade parameters in strabismus.

4.6 Conclusion

There was no significant difference between the BSV subjects and strabismic subjects for saccade latency and gain when targets were presented to both eyes. Saccades were of similar amplitude in each eye in the BSV group with only small divergent disconjugacy. Disconjugacy for exotropic subjects was also divergent but larger than for the BSV subjects. The esotropic subjects had a mixture of convergent and divergent disconjugacy with a tendency for increasing convergent disconjugacy for saccades towards the strabismic eye. All saccade parameters were therefore comparable to previously reported literature

All subjects were compliant with the task allowing successful recording and analysis of saccades and all agreed to take part, and were included in, further experiments described in Chapters 5 and 6.

Chapter 5

The remote distractor effect in normal binocular single vision

This chapter describes the experiment carried out to assess the remote distractor effect in normal BSV, particularly to determine differences in the effect with the distractor presented to both eyes and one eye only.

5.1 Experiment 4: Binocular and monocular distractors in normal BSV

It has been shown, as described in detail in Chapter 1, Section 1.1.2, that the latency and accuracy of saccades can be altered by the presence of a peripheral target, known as a distractor. Walker, Deubel, Schneider and Findlay (1997) demonstrated that, for horizontal saccades, there was a reciprocal effect on saccade latency and accuracy depending on distractor location (see Figure 5.1). Distractors presented within a window of 20° around the horizontal target axis affected amplitude, but did not influence latency. Distractors presented greater than 20° from this axis increased latency, but had no effect on amplitude. The latency increase reached a peak with distractors presented at the original fixation location.

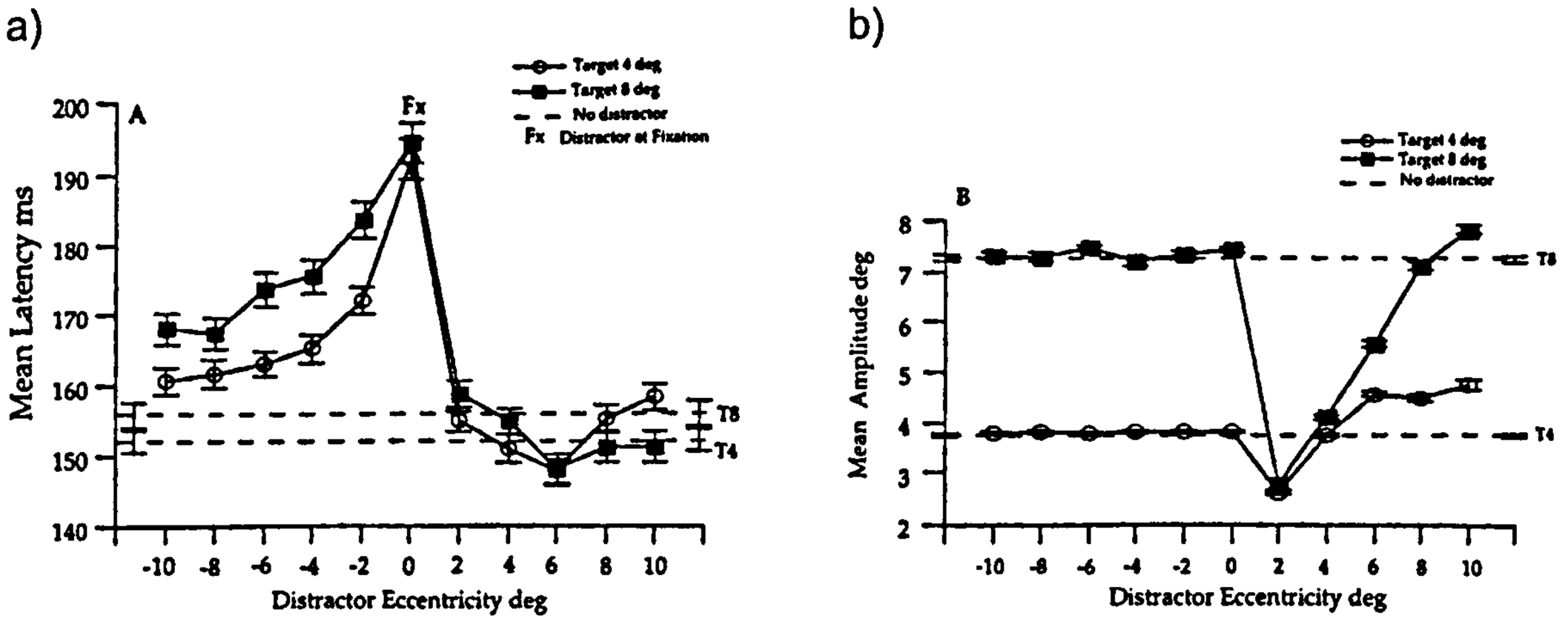


Figure 5.1: Effects of remote distractors on a) saccade latency and b) amplitude. Pooled data for six subjects. Error bars = 1SE. From Walker, Deubel, Schneider and Findlay (1997).

The experimental test condition in previous distractor studies has been for the target and distractor to be presented to both eyes. The exception is a study by Walker, Mannan, Maurer, Pambakian and Kennard (2000), which measured the distractor effect using monocular fixation and distractors presented monocularly in eight normal subjects and

six subjects with hemianopia. Distractors were presented at equal eccentricity in the contralateral hemifield to the target, either 5° or 10°. In the normal subjects they found a small difference in the saccade latency increase for temporal field distractors (15ms) compared to nasal field distractors (7ms), however this was not statistically significant. Due to the nature of the group studied, and with the aim of the study to compare distractors in the blind field with distractors in the seeing field, distractors were not presented at the original fixation location where the maximum effect would be expected. Comparisons were not made to binocular distractor presentations.

On a variety of visual tasks binocular performance is superior to monocular performance, an effect referred to as binocular summation. As this superiority, of the two eyes over one, exceeds that predicted on the basis of statistical considerations alone (i.e. probability summation) binocular summation is thought to reflect neural interaction between the eyes (Blake & Fox, 1973). It is well established that binocular performance is greater than that predicted by probability summation models for threshold tasks such as increment detection, form recognition, acuity and flicker fusion (Blake & Fox, 1973).

Reaction time has been found to reduce with an increase in intensity of the visual stimulus (Hovland, 1936; Steinman, 1944; Bartlett & Macleod, 1954). Smith (1955) found that raising the intensity of a target by 1 log unit decreased reaction time by 25%. Poffenberger (1912) was the first to report that binocular reaction time was faster than monocular reaction time to the same visual stimulus. Travis (1949) used a discrimination task in which subjects were required to identify the break in a Landolt ring. The reaction time binocularly was significantly less than monocular performance. Smith (1955) quantified this, finding that binocular reaction time was 15 to 19% faster than monocular depending on the intensity of stimulus. Differences in reaction time binocularly, monocularly in the dominant eye and monocularly in the non-dominant eye have been compared by Minucci and Connors (1964) over a range of light intensity levels. Overall binocular reaction times were faster than the dominant eye by 6% and faster than the non-dominant eye by 10%.

As distractors hinder saccadic performance it is possible that the presence of distractors in both eyes would have a larger effect on saccade latency and accuracy compared with monocular presentation and this will be studied in this Chapter.

Ocular dominance, first described by Porta (1593) is where the input of one eye is favoured over the other. The dominant eye is thought to be more involved in visual

direction and space localisation (Brod and Hamilton, 1971; Fowler and Stein, 1983). Rombouts, Barkhof, Sprenger, Valk and Scheltens (1996) used functional MRI to establish a basis of ocular dominance. Their results show that the dominant eye activates a larger area of the primary visual cortex than the non-dominant eye.

With respect to programming and characteristics of eye movements, the difference in response of the dominant and non-dominant eye has received very little attention in the literature. Moiseeva, Slavutskaya and Shul'govskii (2000) evaluated lateral differences in saccade latency, measured with electro-oculogram (EOG), and the latency of the peak of rapid pre-saccade potentials, using electroencephalograph (EEG) traces, in response to presentation of visual stimuli to the dominant and non-dominant eyes. No consistent response was found in saccade latency for dominant or non-dominant stimulation. An earlier appearance of EEG potentials in response to stimulation of the dominant eye was found. The authors suggested that this may reflect greater rates of attention disengagements of fixation and faster sensory processing of the peripheral visual stimulus. Potentials immediately preceding the start of the saccades, which reflect the process of motor initiation, were increased during stimulation of the dominant eye suggesting a leading role for this eye in motor preparation in saccades.

Han, Seideman and Lennerstrand (1995), in a study of accommodative vergence movements, found that the gain of accommodative vergence was larger in non-dominant eye stimulation than dominant eye stimulation.

The aims of the present study were to replicate the binocular distractor effect in our laboratory set-up, and compare it with that described by Walker, Deubel, Schneider and Findlay (1997). Secondly, to investigate this further by comparing the effects of distractor presentations to the dominant eye, non-dominant eye or to both eyes. This has not previously been investigated and it is unknown whether the dominant eye has a greater input to saccade planning than the non-dominant eye, or whether differences in monocular and binocular distractor presentation exist. The unique design of the LCP shutter system for dissociation allowed presentation of distractors monocularly whilst the fixation target was presented binocularly to determine whether a significant difference in saccade latency or accuracy was found compared to binocular distractor presentations.

5.1.1 Hypotheses

1. When distractors are presented to both eyes the reciprocal effect of distractors on saccade latency and gain, reported by Walker, Deubel, Schneider and Findlay (1997) will be replicated in our laboratory set-up.
2. The effect of distractors on saccade *latency* when presented to the dominant eye will be greater than when presented to the non-dominant eye.
3. The effect of distractors on saccade *gain* when presented to the dominant eye will be greater than when presented to the non-dominant eye.
4. The effect of distractors on saccade *latency* when presented binocularly will be greater than when presented monocularly.
5. The effect of distractors on saccade *gain* when presented binocularly will be greater than when presented monocularly.

5.2 Methods

5.2.1 Participants

Five subjects with normal corrected visual acuity, bifoveal BSV and stereoacuity of at least 60" of arc using the TNO test, were recruited from a student population. The mean age of the subjects was 20.6 years (range 19.0 - 21.8 years). Table 5.1 shows details of the subjects. All were naive to the purpose of the study and had only had one previous experience of eye movement recording as reported in Experiment 3 of Chapter 4. The characteristics of saccades in this group of subjects have been described earlier in Experiment 3.

Subject	Age (years)	VA (logMAR)		Refractive correction		Cover Test	Prism Cover Test at 114cm (Δ)	Stereo (sec of arc)	Dominant eye
		RE	LE	RE	LE				
1	19.9	-0.1	0.0	plano	plano	exophoria	4 BI	60	Right
2	21.8	-0.1	-0.1	plano	plano	exophoria	2 BI	60	Right
3	21.3	-0.1	-0.1	plano	plano	exophoria	4 BI	60	Right
4	19.0	-0.1	-0.1	-0.50	-0.50	esophoria	4 BO	30	Left
5	21.2	0.0	-0.1	-5.50	-5.00	exophoria	2 BI	60	Left

Table 5.1: Characteristics of the five subjects. VA = logMAR visual acuity, RE = right eye, LE = left eye, Δ = prism dioptre, BI = prism base in, BO =prism base out.

5.2.2 Apparatus

The laboratory was set-up as described in Chapter 2, Figure 2.4. Eye movements were recorded using the Skalar infrared limbal tracker and head movements were restricted by use of chin and cheek rests. The eye movement data was stored on disk and analysed off-line.

A 1° cross target (see Figure 5.2) was presented by back projection from projector 1 in the centre of a flat translucent screen 114cm from the subject's eye. The mirror galvanometer sited in front of the projector was used to move the target randomly to either 4° or 8° eccentricities along the horizontal axis. This target was visible to both eyes at all times.

Projector 2 back projected a distractor onto the screen. The distractor consisted of an unfilled circle, diameter 1.5° (see Figure 5.2) which, when presented, appeared for 200ms simultaneously with the onset of the target. In the experiment, three distractor conditions were used; distractor to both eyes simultaneously, distractor to the dominant eye only and distractor to the non-dominant eye only. Distractor presentation to one or both eyes was controlled by four LCP shutters, one positioned between the lens and the mirror galvanometer of each projector and one positioned in front of each of the subject's eyes. Alteration of the timing of the four shutter openings in relation to each other allowed dissociation of the eyes and hence presentation of the target to both eyes, and the distractor to one eye or both eyes, depending on the condition (see Chapter 2, Figures 2.8 and 2.9).

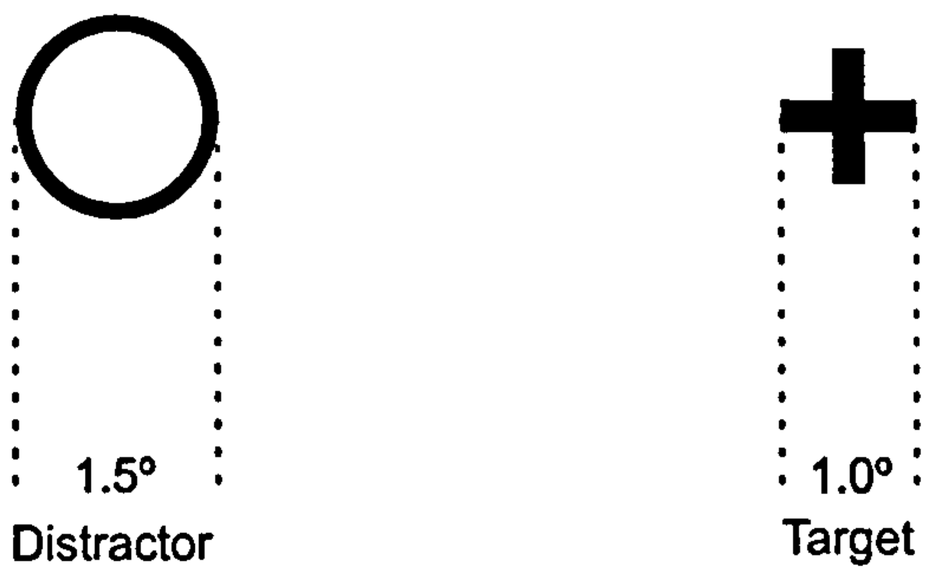


Figure 5.2: The appearance and dimensions of distractor and target.

The target size, distractor size and distractor duration were selected following a pilot study run on two subjects (sizes: 1°, 1.5° and 2°; durations: 100ms and 200ms). Those selected, 1.5° and 200ms, gave the greatest effect and were comparable with Walker, Deubel, Schneider and Findlay (1997). The targets were also considered to be of an appropriate size to allow visibility by subjects with mild to moderate amblyopia in later studies.

A stationary, blurred, random dot background, of luminance 2cd/m^2, was back projected by projector 3 and was visible to both eyes under all experimental conditions (Figure 5.3).

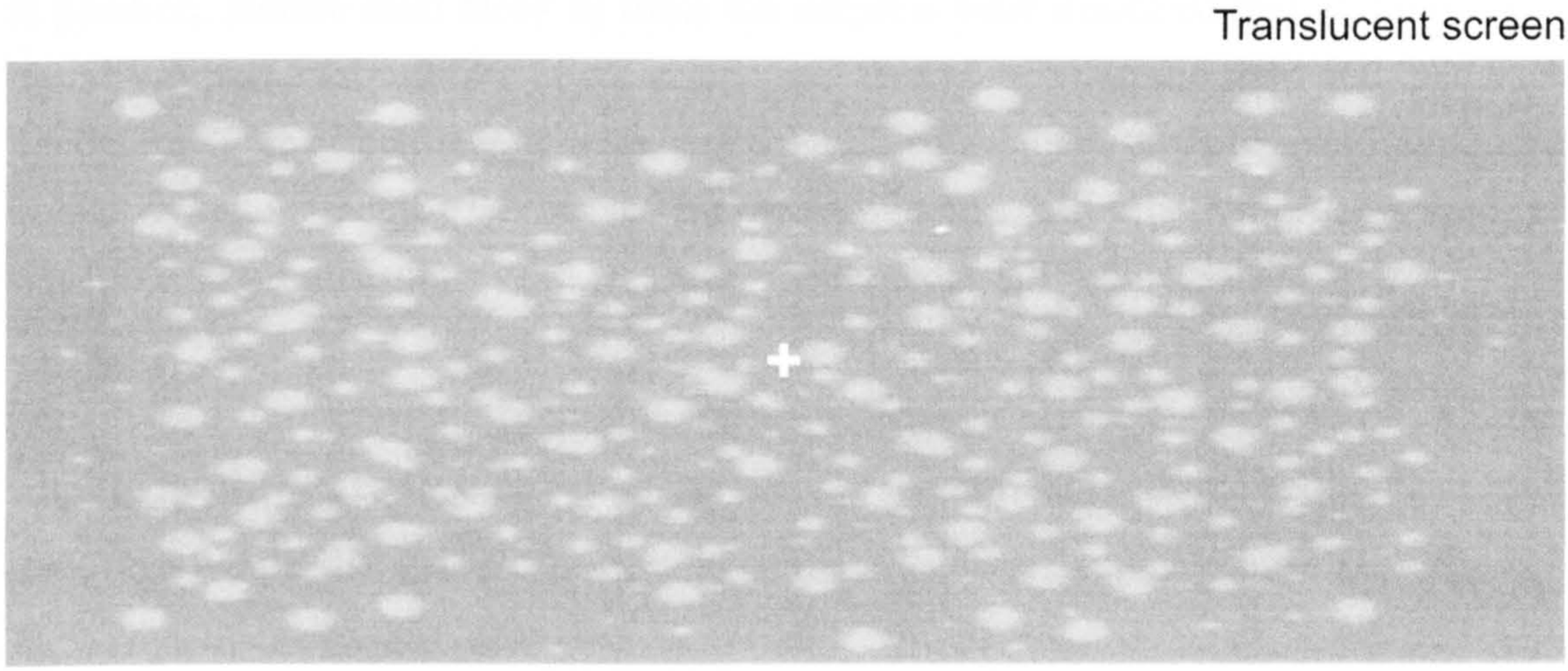


Figure 5.3: Image of the stationary background back projected onto translucent screen, with the 1° target cross.

5.2.3 Design of the experiment

The experiment was a repeated measures design, with the independent variables being target position (4° or 8°), distractor presentation to the dominant, non-dominant or both eyes and distractor position (0, ±2°, ±4°, ±6°,±8°, ±10°). Dependent variables were the saccade latency and saccade gain.

To guard against effects of learning or fatigue the independent variables were counterbalanced by randomisation.

5.2.4 Procedure

A clinical examination was initially performed to determine the presence of normal bifoveal BSV, level of visual acuity and eye dominance. Ocular dominance was

determined using the hole-in-the-card test bi-manually (Walls, 1956). This was carried our prior to Experiment 3 and up to one week before this current experiment.

The eye movement recordings were carried out over three testing sessions, each one lasting for approximately 45 minutes. This was because longer recording sessions would have lead to fatigue and could have reduced the number of saccades for analysis. The three sessions were completed over a maximum period of ten days.

For each eye movement recording session the subjects were seated in a comfortable office chair with the Skalar infrared eye movement recorder and LCP shutters clamped in position. Before each block of trials the subjects were informed that all targets would initially appear in the centre of the screen and always move to the right and then back to the centre. This direction was maintained for all subsequent trials to avoid any increase in latency on distractor trials caused by the additional discrimination process required to select the target direction (Walker, Deubel, Schneider & Findlay, 1997).

Pursuit eye movements, generated using a sinusoidal target motion of 0.32Hz of amplitude ±12°, were used to calibrate the eye movement recorder before each trial, as described in Chapter 2, Figure 2.3.

Figure 5.4 shows the target and distractor positions. The target was presented centrally and, to avoid anticipation, there was a random period (500 to 1200ms) before the target disappeared and immediately reappeared at either 4° or 8° on the horizontal axis for 500ms (nominally zero gap). The target then returned to the centre point before the next trial. In most trials a distractor appeared simultaneously with the onset of the 4° or 8° targets for 200ms. The eccentricity of the distractor varied randomly between -10, -8, -6, -4, -2, 0, +2, +4, +6, +8 and +10° along the horizontal axis, where positive numbers represent distractors ipsilateral to the target and negative numbers represent distractors contralateral to the target. Zero indicates distractors presented at the original fixation point.

All three distractor conditions (distractor to both eyes, dominant eye and non-dominant eye) were presented during each of the three recording sessions. The order of the conditions was randomised between sessions. In 60 out of the 720 saccades collected (20 during each distractor condition) no distractor was presented. Twenty saccades at each distractor eccentricity were collected for each distractor condition.

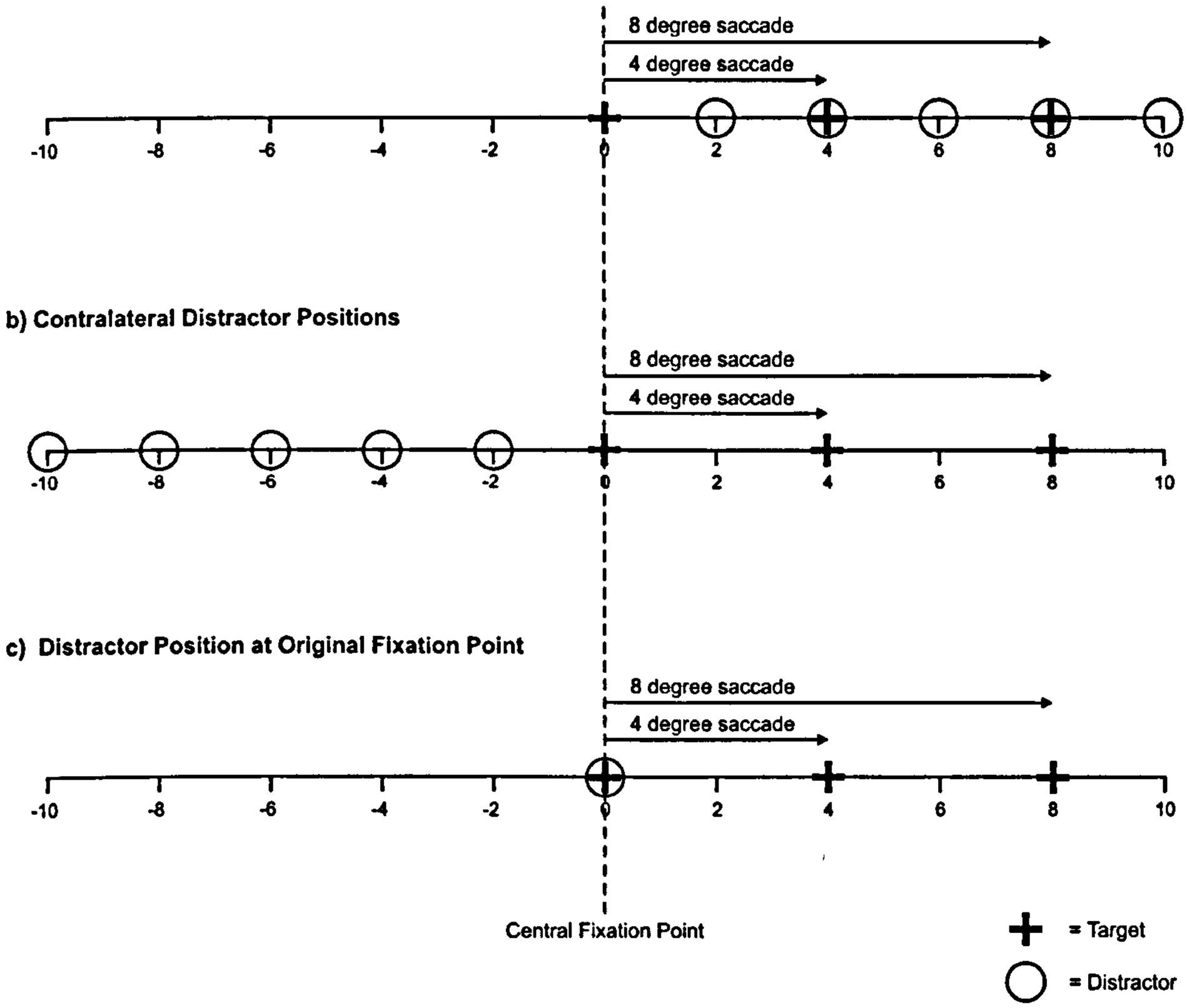


Figure 5.4: Schematic diagram of target and distractor positions.

Subjects were instructed to look directly at the centre of the small target cross, positioned in the middle of the screen and, when it jumped to the right, to move their eyes as quickly and accurately as possible to continue looking at the centre of the cross. They were told not to anticipate the target movement and that they should only move their eyes when movement had occurred. They were told that sometimes a circle (i.e. the distractor) may appear anywhere on the screen, but this should be ignored at all times.

5.3 Results

Saccadic eye movement data from the dominant eye was analysed using Visual Basic computer software. Each saccade was checked visually to confirm correct detection of the primary saccade. Mean saccade latency and gain for each individual subject was calculated for each distractor eccentricity and for each of the three types of distractor. Saccades with latency <80ms were excluded as they were considered to be anticipatory (Fischer & Webber, 1993) and saccades with latency >450ms were excluded as they were not considered to be visually triggered (Walker, Deubel, Schneider & Findlay,

1997). In all subjects a small number of saccades could not be analysed due to blinks or incorrect fixation. A total of 14% of saccades was therefore excluded from the analysis. The data was then transferred to Excel spread sheets for further analysis.

The results are presented in terms of the distractor effect on saccade latency (Section 5.3.1) and saccade gain (Section 5.3.2). In each of these sections the response without distractors are firstly presented, followed by the response with distractor in monocular and binocular conditions.

5.3.1 Saccade Latency

Latency without distractors

The mean saccade latency for target presentations without distractors for each subject during each distractor condition (i.e. during testing of distractors to dominant eye, non-dominant eye and both eyes) is shown in the last column of Tables 5.2a and b. To determine whether saccade latency was different during the three test conditions and for 4° and 8° saccades, a two-factor repeated measures analysis of variance (ANOVA) was performed. The two factors were: distractor condition (dominant eye, non-dominant eye, both eyes) and target amplitude (4° and 8°). There was no significant difference in saccade latency for saccades without distractors in the three test conditions [$F(2,8)=0.145$, $p>0.05$], and no significant difference for the two saccade amplitudes [$F(1,4)=0.042$, $p>0.05$] There were no significant interactions between the factors (ANOVA details are shown in Appendix 7.1). Therefore there was no difference in saccade latency without distractors throughout the experiment. The mean saccade latency for no distractor trials from the three test conditions and both target amplitudes were therefore pooled and are shown in Table 5.3. These mean values for saccade latency without distractors are used to compare latency with distractor presentations and are shown as horizontal lines in Figure 5.5a and b.

A one-sample t test compared the mean latency for the group reported in this current study with the mean saccade latency without distractors reported by Walker, Deubel, Schneider and Findlay (1997), which revealed no significant difference between the studies (4° targets: $t = -0.375$, $df = 4$, $p>0.05$, 8° targets: $t= -0.730$, $df = 4$, $p>0.05$). Details of t-tests are shown in Appendix 7.2.

Table 5.2a: The effect of distractors on saccade latency for 4 degree saccades - mean data for each subject

Distractor dominant eye												
Distractor position	-10	-8	-6	-4	-2	0	2	4	6	8	10	no distractor
Subject 1	150.80	153.39	148.50	162.62	171.00	260.21	171.40	156.07	151.88	144.82	144.86	144.35
Subject 2	156.46	137.02	148.21	144.38	156.33	170.00	148.93	140.49	147.71	143.66	149.06	141.43
Subject 3	157.36	156.88	159.06	167.74	163.18	180.28	154.75	153.86	156.00	163.89	158.00	149.88
Subject 4	180.73	181.11	175.31	186.18	192.25	202.08	185.93	182.08	191.91	170.35	172.40	166.31
Subject 5	165.00	159.32	164.46	166.07	189.06	202.19	166.25	162.88	160.31	163.02	155.00	152.89
Mean	**162.07**	**157.54**	**159.11**	**165.40**	**174.37**	**202.95**	**165.45**	**159.08**	**161.56**	**157.15**	**155.86**	**150.97**
SD	**11.59**	**15.79**	**11.43**	**14.90**	**15.79**	**34.93**	**14.52**	**15.21**	**17.60**	**12.12**	**10.56**	**9.68**
SE	**5.18**	**7.06**	**5.11**	**6.66**	**7.06**	**15.62**	**6.49**	**6.80**	**7.87**	**5.42**	**4.72**	**4.33**
Distractor non-dominant eye												
Distractor position	-10	-8	-6	-4	-2	0	2	4	6	8	10	no distractor
Subject 1	151.02	155.71	146.00	155.63	156.96	198.06	151.56	141.75	147.92	143.10	148.37	146.07
Subject 2	139.03	133.62	137.81	137.19	154.29	171.94	134.32	136.07	133.02	130.42	150.69	131.50
Subject 3	157.50	152.08	159.24	153.89	159.44	186.25	163.43	155.83	155.90	160.42	162.04	141.27
Subject 4	184.29	197.06	195.52	190.00	192.00	223.25	193.85	190.00	192.50	184.72	180.42	171.16
Subject 5	150.17	156.94	163.33	171.25	166.28	178.06	161.26	153.25	154.44	155.00	162.39	152.81
Mean	**167.23**	**177.00**	**179.43**	**180.63**	**179.14**	**191.51**	**177.56**	**171.63**	**173.47**	**169.86**	**171.40**	**161.99**
SD	**24.13**	**28.37**	**22.76**	**13.26**	**18.19**	**20.26**	**23.04**	**25.99**	**26.91**	**21.02**	**12.75**	**12.97**
SE	**10.79**	**12.69**	**10.18**	**5.93**	**8.13**	**9.06**	**10.30**	**11.62**	**12.03**	**9.40**	**5.70**	**5.80**
Distractor both eyes												
Distractor position	-10	-8	-6	-4	-2	0	2	4	6	8	10	no distractor
Subject 1	150.25	146.53	149.75	154.72	157.42	245.71	154.58	155.28	146.46	129.76	124.11	148.48
Subject 2	139.09	149.17	148.61	139.17	163.33	178.39	151.01	138.69	130.21	134.60	134.55	130.25
Subject 3	154.67	159.58	163.39	172.00	182.24	213.75	175.89	147.78	156.07	144.80	157.71	142.23
Subject 4	186.72	187.54	192.47	198.33	207.33	229.38	210.83	176.86	172.22	170.17	180.33	174.83
Subject 5	161.43	159.50	155.94	149.17	171.66	212.41	157.47	143.32	134.31	142.26	150.50	145.85
Mean	**158.43**	**160.46**	**162.03**	**162.68**	**176.40**	**215.93**	**169.96**	**152.39**	**147.85**	**144.32**	**149.44**	**148.33**
SD	**17.78**	**16.25**	**18.00**	**23.22**	**19.65**	**24.97**	**24.79**	**14.99**	**17.02**	**15.65**	**21.72**	**16.37**
SE	**7.95**	**7.27**	**8.05**	**10.38**	**8.79**	**11.17**	**11.08**	**6.70**	**7.61**	**7.00**	**9.71**	**7.32**

Table 5.2b: The effect of distractors on saccade latency for 8 degree saccades - mean data for each subject

Distractor dominant eye												
Distractor position	-10	-8	-6	-4	-2	0	2	4	6	8	10	no distractor
Subject 1	145.71	145.09	158.66	153.93	155.67	192.95	136.25	148.89	139.17	127.10	134.29	134.06
Subject 2	139.35	146.42	156.43	138.02	153.26	160.75	151.04	137.08	146.98	137.63	159.83	139.95
Subject 3	155.13	149.46	160.91	166.27	167.58	182.00	158.06	160.63	154.29	141.39	162.44	152.00
Subject 4	191.53	199.72	208.25	205.75	220.73	230.25	226.06	179.03	186.00	190.13	190.89	171.25
Subject 5	152.21	160.00	156.86	169.00	180.31	221.56	176.89	160.00	153.73	162.61	166.65	148.13
Mean	**156.79**	**160.14**	**168.22**	**166.59**	**175.51**	**197.50**	**169.66**	**157.13**	**156.03**	**151.77**	**162.82**	**149.08**
SD	**20.35**	**22.89**	**22.45**	**25.08**	**27.47**	**28.56**	**34.75**	**15.57**	**17.84**	**25.03**	**20.16**	**14.23**
SE	**9.10**	**10.24**	**10.04**	**11.22**	**12.29**	**12.77**	**15.54**	**6.96**	**7.98**	**11.19**	**9.02**	**6.36**
Distractor non-dominant eye												
Distractor position	-10	-8	-6	-4	-2	0	2	4	6	8	10	no distractor
Subject 1	143.61	139.46	158.14	145.99	145.24	161.67	143.07	134.83	133.02	140.25	135.83	128.78
Subject 2	144.94	135.83	141.13	137.74	140.67	156.43	131.00	137.19	145.00	127.00	136.12	133.17
Subject 3	158.85	149.36	166.44	165.28	163.39	205.75	158.75	147.36	154.34	142.92	154.15	148.89
Subject 4	209.09	190.71	205.38	213.33	230.21	241.32	239.54	203.81	182.50	190.49	206.23	189.35
Subject 5	158.47	153.21	160.19	169.69	157.73	206.01	160.06	164.56	153.23	158.30	164.88	146.13
Mean	**162.99**	**153.72**	**166.26**	**166.41**	**167.45**	**194.23**	**167.48**	**157.55**	**153.62**	**151.79**	**159.44**	**149.26**
SD	**26.76**	**21.86**	**23.79**	**29.38**	**36.26**	**35.28**	**41.56**	**28.39**	**18.26**	**24.32**	**28.93**	**23.95**
SE	**11.97**	**9.77**	**10.64**	**13.14**	**16.22**	**15.78**	**18.59**	**12.69**	**8.17**	**10.88**	**12.94**	**10.71**
Distractor both eyes												
Distractor position	-10	-8	-6	-4	-2	0	2	4	6	8	10	no distractor
Subject 1	145.03	145.25	146.04	154.33	163.57	176.60	152.63	138.51	131.00	129.48	122.50	129.68
Subject 2	142.01	151.64	154.47	148.00	159.79	171.42	145.21	142.31	139.96	152.58	145.71	152.72
Subject 3	163.49	167.32	159.86	167.83	171.55	208.89	172.50	154.51	145.68	143.44	152.71	147.36
Subject 4	201.84	197.50	206.23	204.28	220.83	240.23	207.08	184.76	175.30	181.14	199.38	183.75
Subject 5	166.13	162.63	159.09	170.28	178.19	248.81	164.06	156.54	141.22	143.75	148.44	148.48
Mean	**163.70**	**164.87**	**165.14**	**168.94**	**178.79**	**209.19**	**168.30**	**155.32**	**146.63**	**150.08**	**153.75**	**152.40**
SD	**23.87**	**20.22**	**23.62**	**21.82**	**24.56**	**35.43**	**24.08**	**18.17**	**16.89**	**19.23**	**28.07**	**19.62**
SE	**10.68**	**9.04**	**10.56**	**9.76**	**10.98**	**15.85**	**10.77**	**8.13**	**7.55**	**8.60**	**12.55**	**8.77**

Mean saccade latency with no distractor		
Subject	**4° target**	**8° degree**
1	145.67	133.37
2	135.63	141.44
3	145.00	148.85
4	171.48	179.81
5	151.04	147.73
Mean	**149.76**	**150.24**
SD	**13.35**	**17.64**
SE	**5.97**	**7.89**

Table 5.3: Mean saccade latency of saccades made with no distractor for individual subjects. SD = standard deviation, SE = standard error.

Distractors at fixation

Tables 5.2a and b show the mean saccade latency with distractors to both eyes, dominant eye and non-dominant eye, at each distractor position for each subject.

Figure 5.5 shows the mean saccade latency pooled for the group, plotted as a function of distractor eccentricity with distractors presented to both eyes, the dominant eye and the non-dominant eye. The group mean latency ±1standard error without distractors is shown in this figure as horizontal lines for comparison.

A similar response to distractors was observed in all subjects for all distractor conditions, such that saccade latency was increased maximally when distractors appeared at fixation and increased in the contralateral non-target hemifield. Ipsilateral distractors for 4° saccades showed a small increase in saccade latency when presented to the dominant eye and non-dominant eye, but were unaffected when the distractor was presented to both eyes. For 8° saccades in all conditions, ipsilateral distractors did not affect latency.

When comparing the three types of distractor presentation, a slightly greater effect was demonstrated with the distractor at fixation to both eyes, compared to monocular presentation in all subjects. From the pooled data for 4° target eccentricity (shown in Table 5.4a) the saccade latency increased by 65.9ms, compared to the no distractor condition, when the distractor was presented to both eyes simultaneously, 53.0ms when presented to the dominant eye and 41.5ms when presented to the non-dominant eye.

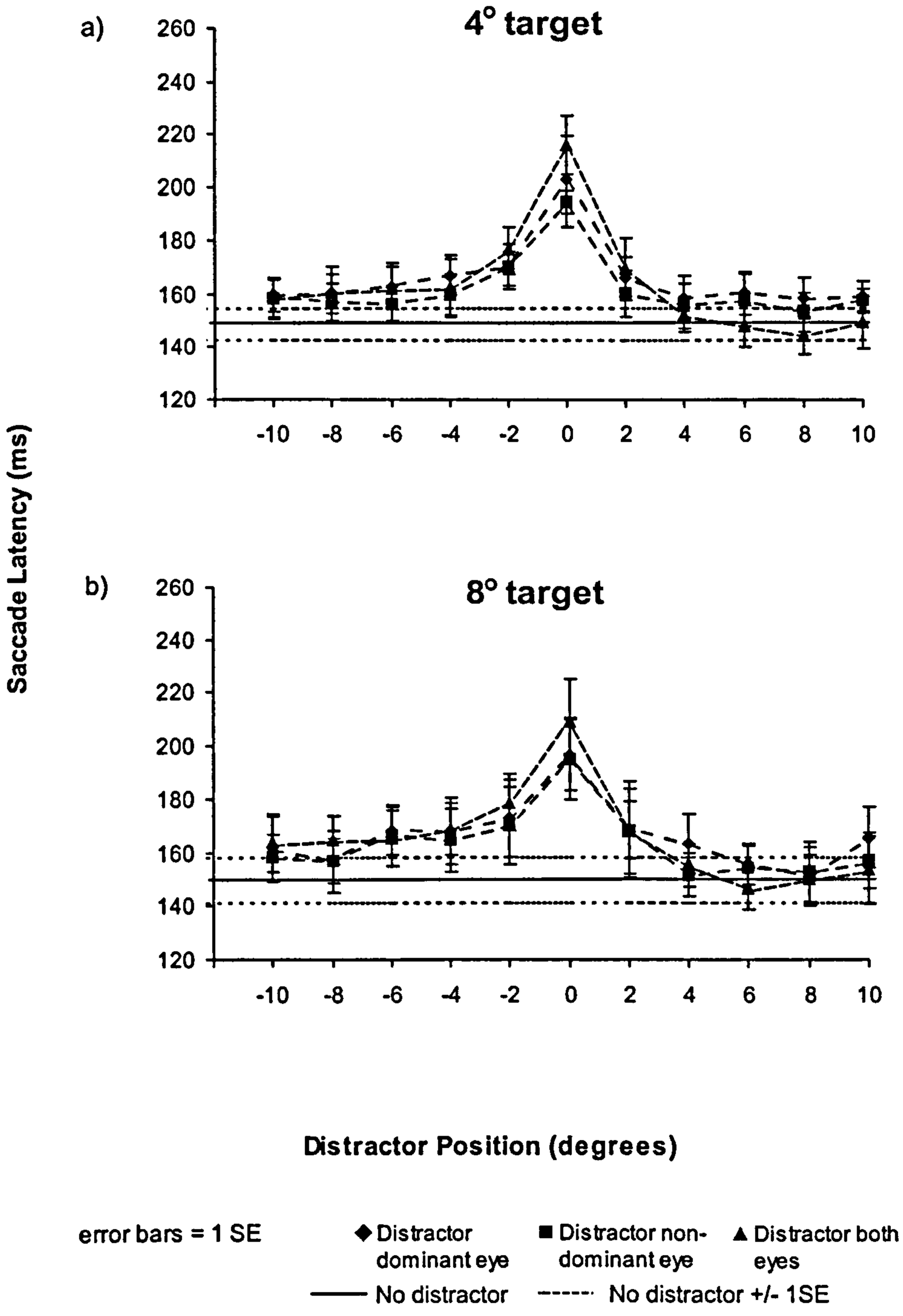


Figure 5.5: Effect of distractors on saccade latency, a) target presented at 4°, b) target presented at 8°. Pooled data for five subjects with normal BSV is shown. SE = standard error.

For 8° target eccentricity (Table 5.4b), saccade latency increased by 59.2ms when the distractor was presented to both eyes simultaneously, 47.5ms when presented to the dominant eye and 44.2ms when presented to the non-dominant eye. To establish whether this difference between distractors to the dominant, non-dominant or both eyes was significant, a three-factor repeated measures ANOVA was performed. The three factors were: eye viewing the distractor (dominant, non-dominant or both eyes), target

amplitude (4° and 8°) and distractor (no distractor or distractor at fixation). The results showed that there was no significant difference between the three distractor conditions at fixation [F(2,8)=2.531, p>0.05]. Also, the effect was not significantly different for target amplitude [F(1,4)=0.014, p>0.05]. The only effect was for presence or absence of a distractor at fixation [F(1,4)=65.00, p<0.01]. No significant interactions were found between any of the three factors with the highest level of significance for interactions being F(2,8)=1.949, P>0.05). ANOVA details are shown in Appendix 7.3.

A one-sample t-test compared the mean latency with distractors at fixation for the group reported in this current study with the mean saccade latency with distractors at fixation reported by Walker, Deubel, Schneider and Findlay (1997), which revealed no significant difference between the studies (4° targets: t = 2.008, df = 4, p>0.05, 8° targets: t= 0.990, df = 4, p>0.05). Details of t-tests are shown in Appendix 7.2.

Distractors contralateral and ipsilateral to the target

For Hypothesis 1, to show whether the effect on latency differed between contralateral and ipsilateral distractors and, for Hypotheses 2 and 4, to test for differences in saccade latency with distractors presented to the dominant, non-dominant and both eyes, a four-factor repeated measures ANOVA was performed. The four factors were; eye viewing the distractor (dominant, non-dominant or both eyes), target amplitude (4° and 8°), side of distractor (contralateral or ipsilateral) and position of distractor (2°, 4°, 6°, 8° and 10°). This revealed no significant effect for target amplitude [F(1,4)=0.225, p>0.05], or which eye was viewing the distractor [F(2,8)=0.535, p>0.05]. Contralateral distractors gave significantly greater saccade latencies than ipsilateral distractors, [F(1,4)=58.176, p<0.01]. Distractor position was also significant [F(4,16)=14.959, p<0.01]. When considering interactions of the factors, there was a significant interaction between eye viewing the distractor and the side of distractor [F(2,8)=22.832, p<0.01]. ANOVA details are shown in Appendix 7.4.

From Figure 5.5 it would appear that this significant interaction reflects a larger difference in ipsilateral and contralateral distractors for the both eyes condition. To test this, data from the both eyes condition was removed from the four-factor ANOVA and the significance disappeared confirming this assumption. ANOVA details are shown in Appendix 7.5.

a)

Distractor condition	Distractor position (degrees)										
	-10	-8	-6	-4	-2	0	2	4	6	8	10
Dominant eye	12.07	7.54	9.11	15.40	24.37	52.95	15.45	9.08	11.56	7.15	5.86
Non-dom eye	17.23	27.00	29.43	30.63	29.14	41.51	27.56	21.63	23.47	19.86	21.40
Both eyes	8.43	10.46	12.03	12.68	26.40	65.93	19.96	2.39	-2.15	-5.68	-0.56

b)

Distractor condition	Distractor position (degrees)										
	-10	-8	-6	-4	-2	0	2	4	6	8	10
Dominant eye	6.79	10.14	18.22	16.59	25.51	47.50	19.66	7.13	6.03	1.77	12.82
Non-dom eye	12.99	3.72	16.26	16.41	17.45	44.23	17.48	7.55	3.62	1.79	9.44
Both eyes	13.70	14.87	15.14	18.94	28.79	59.19	18.30	5.32	-3.37	0.08	3.75

Table 5.4: Mean difference (pooled data for five subjects) in saccade latency (ms) between no distractor presentation and distractor presentation at each eccentricity for each distractor condition. a) 4° target stimulus, b) 8° target stimulus. Positive values represent an increase and negative values a decrease in saccade latency with distractors compared to the no distractor condition.

5.3.2 Saccade Gain

Saccade gain was taken to represent a measure of saccade accuracy, calculated by dividing the saccade amplitude by the target amplitude, hence a gain of 1 equals a saccade precisely reaching the target, >1 equals a hypermetric saccade and <1 equals a hypometric saccade.

Gain without distractors

The mean saccade gain for target presentations without distractors for each subject during each distractor test session is shown in the last column of Tables 5.5a & b. To determine whether saccade gain was different during the three test sessions, and for 4° and 8° saccades, a two-factor repeated measures ANOVA was performed. The two factors were: distractor condition (dominant eye, non-dominant eye, both eyes) and target amplitude (4° and 8°). There was no significant difference in saccade gain for saccades without distractors in the three test sessions [$F(2,8)=0.470$, $p>0.05$]. As expected, a significant difference for the two target amplitudes was found [$F(1,4)=7.789$, $p<0.05$] showing that gain was significantly less for 8° targets than 4° targets. There were no interactions between the factors. The mean saccade gain for all conditions was therefore pooled and is shown for each amplitude in Table 5.6. ANOVA details are shown in Appendix 7.6.

Table 5.5a: The effect of distractors on saccade gain for 4 degree saccades - mean data for each subject

Distractor dominant eye												
Distractor position	-10	-8	-6	-4	-2	0	2	4	6	8	10	no distractor
Subject 1	0.994	0.896	1.056	1.031	1.278	0.968	0.792	0.897	1.121	1.387	1.354	1.062
Subject 2	1.077	1.060	1.018	1.107	1.052	1.073	0.885	0.994	1.207	1.259	1.317	0.988
Subject 3	1.016	1.002	0.944	0.959	0.911	0.921	0.968	1.055	1.200	1.158	1.232	1.018
Subject 4	0.968	0.914	0.955	1.017	1.040	0.978	0.906	0.960	1.213	1.033	0.991	0.916
Subject 5	1.007	0.944	1.015	1.013	0.993	0.991	0.816	0.967	1.343	1.062	1.311	0.988
Mean	**1.012**	**0.963**	**0.998**	**1.025**	**1.055**	**0.986**	**0.873**	**0.975**	**1.217**	**1.180**	**1.241**	**0.994**
SD	**0.040**	**0.068**	**0.047**	**0.053**	**0.137**	**0.055**	**0.071**	**0.057**	**0.080**	**0.146**	**0.147**	**0.053**
SE	**0.018**	**0.030**	**0.021**	**0.024**	**0.061**	**0.025**	**0.032**	**0.026**	**0.036**	**0.065**	**0.066**	**0.024**
Distractor non-dominant eye												
Distractor position	-10	-8	-6	-4	-2	0	2	4	6	8	10	no distractor
Subject 1	1.161	1.030	1.123	1.018	1.214	0.769	1.058	0.982	1.339	1.483	1.658	0.980
Subject 2	1.099	1.100	1.115	1.019	0.983	1.116	0.926	1.071	1.620	1.407	1.549	1.085
Subject 3	0.931	1.004	0.961	0.965	0.940	0.957	0.952	0.985	1.160	1.119	1.406	0.991
Subject 4	0.995	0.964	0.984	0.984	0.957	0.974	0.928	0.921	1.201	1.116	0.978	0.935
Subject 5	1.084	1.077	1.002	1.029	1.054	1.004	0.895	1.017	1.143	1.112	1.174	1.077
Mean	**1.054**	**1.035**	**1.037**	**1.003**	**1.029**	**0.964**	**0.952**	**0.995**	**1.243**	**1.247**	**1.353**	**1.013**
SD	**0.091**	**0.055**	**0.076**	**0.027**	**0.112**	**0.125**	**0.063**	**0.055**	**0.105**	**0.182**	**0.277**	**0.065**
SE	**0.041**	**0.024**	**0.034**	**0.012**	**0.050**	**0.056**	**0.028**	**0.024**	**0.047**	**0.081**	**0.124**	**0.029**
Distractor both eyes												
Distractor position	-10	-8	-6	-4	-2	0	2	4	6	8	10	no distractor
Subject 1	1.122	1.110	1.263	1.167	1.216	1.107	0.868	1.082	1.336	1.863	2.022	0.982
Subject 2	1.039	1.093	1.070	1.102	1.064	1.047	0.751	1.083	1.404	1.637	2.040	1.078
Subject 3	0.993	0.957	0.924	1.084	1.063	1.003	0.745	1.035	1.328	1.598	1.864	0.979
Subject 4	0.931	0.974	0.984	0.992	1.000	1.025	0.837	1.109	1.287	1.217	1.168	0.939
Subject 5	1.062	1.128	1.104	0.975	1.088	0.941	0.705	1.081	1.570	1.706	2.033	1.103
Mean	**1.029**	**1.053**	**1.069**	**1.064**	**1.086**	**1.025**	**0.781**	**1.078**	**1.385**	**1.604**	**1.825**	**1.016**
SD	**0.072**	**0.080**	**0.130**	**0.080**	**0.080**	**0.061**	**0.068**	**0.027**	**0.112**	**0.239**	**0.375**	**0.071**
SE	**0.032**	**0.036**	**0.058**	**0.036**	**0.036**	**0.027**	**0.031**	**0.012**	**0.050**	**0.107**	**0.168**	**0.032**

Table 5.5b: The effect of distractors on saccade gain for 8 degree saccades - mean data for each subject

Distractor dominant eye												
Distractor position	-10	-8	-6	-4	-2	0	2	4	6	8	10	no distractor
Subject 1	0.873	0.890	0.889	0.827	0.856	0.752	0.748	0.703	0.770	0.803	0.922	0.813
Subject 2	0.914	0.882	0.934	0.880	0.917	0.973	0.737	0.836	0.808	0.927	0.985	0.991
Subject 3	0.883	0.962	0.947	0.934	0.964	0.944	0.906	0.897	0.861	0.922	0.986	0.924
Subject 4	0.908	0.941	0.963	0.987	0.986	0.990	0.649	0.549	0.761	0.959	0.996	0.973
Subject 5	0.926	0.984	0.938	0.925	0.948	0.932	0.656	0.709	0.776	0.902	0.910	0.982
Mean	**0.901**	**0.932**	**0.934**	**0.911**	**0.934**	**0.918**	**0.739**	**0.739**	**0.795**	**0.903**	**0.960**	**0.936**
SD	**0.022**	**0.045**	**0.028**	**0.060**	**0.051**	**0.095**	**0.104**	**0.135**	**0.041**	**0.059**	**0.041**	**0.074**
SE	**0.010**	**0.020**	**0.012**	**0.027**	**0.023**	**0.043**	**0.046**	**0.060**	**0.018**	**0.027**	**0.018**	**0.033**
Distractor non-dominant eye												
Distractor position	-10	-8	-6	-4	-2	0	2	4	6	8	10	no distractor
Subject 1	1.014	0.916	0.924	0.906	0.920	0.876	0.833	0.891	0.937	0.982	0.972	0.877
Subject 2	0.970	1.016	0.970	0.890	0.900	0.991	0.818	0.866	1.055	0.965	1.069	0.930
Subject 3	0.916	0.839	0.871	0.878	0.986	0.959	0.909	0.822	0.880	0.913	1.002	0.918
Subject 4	0.853	0.885	0.988	0.993	0.936	0.953	0.758	0.706	0.794	0.916	0.991	0.909
Subject 5	1.021	1.020	1.140	1.081	1.050	0.980	0.862	0.823	0.929	0.968	1.053	1.005
Mean	**0.955**	**0.935**	**0.978**	**0.950**	**0.958**	**0.952**	**0.836**	**0.822**	**0.905**	**0.949**	**1.017**	**0.928**
SD	**0.071**	**0.080**	**0.101**	**0.086**	**0.060**	**0.045**	**0.056**	**0.071**	**0.073**	**0.032**	**0.042**	**0.048**
SE	**0.032**	**0.036**	**0.045**	**0.039**	**0.027**	**0.020**	**0.025**	**0.032**	**0.033**	**0.014**	**0.019**	**0.021**
Distractor both eyes												
Distractor position	-10	-8	-6	-4	-2	0	2	4	6	8	10	no distractor
Subject 1	0.914	0.962	1.043	1.054	1.02	0.853	0.731	0.715	0.85	0.894	1.138	0.89
Subject 2	0.892	0.924	0.938	0.974	0.957	0.981	0.436	0.652	0.776	0.988	1.084	0.911
Subject 3	0.992	0.974	0.979	0.969	0.982	1.008	0.591	0.597	0.747	0.964	1.098	0.944
Subject 4	0.967	0.983	0.977	0.978	1.032	1.009	0.666	0.568	0.798	0.931	1.138	0.933
Subject 5	1.032	1.02	0.989	1.055	1.069	1.096	0.52	0.615	0.841	1.066	1.225	1.022
Mean	**0.959**	**0.973**	**0.985**	**1.006**	**1.012**	**0.989**	**0.589**	**0.629**	**0.802**	**0.969**	**1.137**	**0.940**
SD	**0.057**	**0.035**	**0.038**	**0.044**	**0.044**	**0.088**	**0.117**	**0.057**	**0.043**	**0.065**	**0.055**	**0.050**
SE	**0.026**	**0.016**	**0.017**	**0.020**	**0.019**	**0.039**	**0.052**	**0.025**	**0.019**	**0.029**	**0.025**	**0.023**

Mean saccade gain with no distractor		
Subject	**4° target**	**8° target**
1	0.978	0.883
2	1.046	0.942
3	0.999	1.075
4	0.931	0.953
5	1.052	1.001
Mean	**1.001**	**0.971**
SD	**0.045**	**0.072**
SE	**0.020**	**0.029**

Table 5.6: Mean saccade gain of individual subjects for saccades made with no distractor presentation. SD = standard deviation, SE = standard error.

Distractors ipsilateral and contralateral to the target

Tables 5.5a and b show the mean saccade gain with distractors in both eyes, dominant eye and non-dominant eye at each distractor position for each subject. Figure 5.6 shows the mean saccade gain pooled for the group plotted as a function of distractor eccentricity with distractors presented for each distractor condition. The group mean gain without distractors at 4° and 8° are shown in this figure as horizontal lines for comparison. Table 5.7 shows the group mean difference in gain for saccades made with and without distractors at each eccentricity.

A similar response to distractors was observed in all subjects for all distractor presentations, such that accuracy was unaffected by contralateral distractors, but was affected by ipsilateral distractors. With the distractor between fixation and the target the saccade was hypometric, whereas with the distractor at greater amplitudes to the target, saccades were hypermetric. From the pooled data for 4° and 8° target presentations, gain decreased maximally when the distractor was at 2°, i.e. distractor between fixation and the target. Saccade gain increased maximally when the distractor was at 10°, i.e. with the distractor at greater amplitudes than the target.

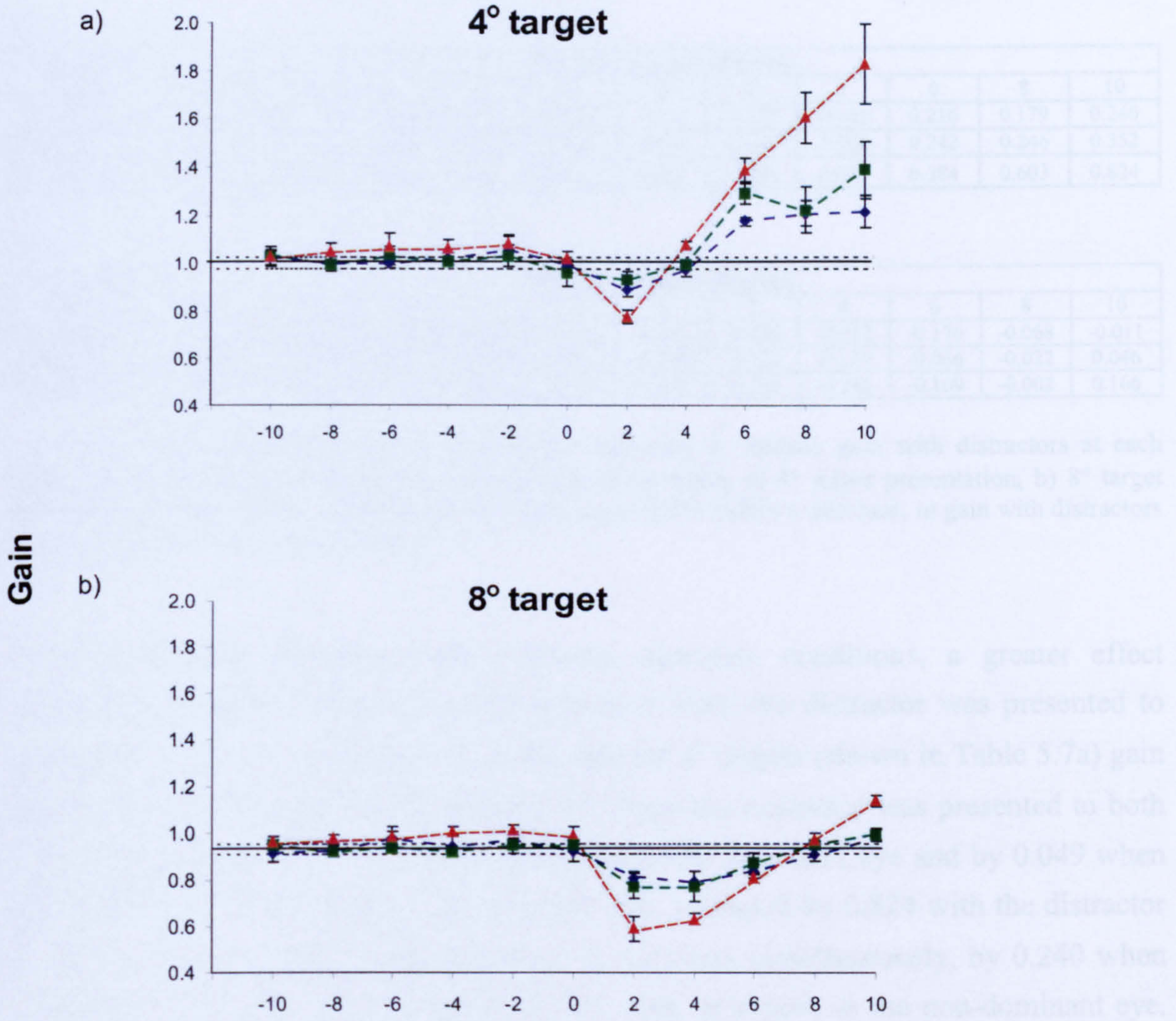


Figure 5.6: Effect of distractors on saccade gain, a) target presented at 4°, b) target presented at 8°. Pooled data for five subjects with normal BSV. SE = standard error.

a)

Distractor condition	Distractor position (degrees)										
	-10	-8	-6	-4	-2	0	2	4	6	8	10
Dominant eye	0.011	-0.038	-0.003	0.024	0.054	-0.015	-0.128	-0.026	0.216	0.179	0.240
Non-dom eye	0.053	0.034	0.036	0.002	0.028	-0.037	-0.049	-0.006	0.242	0.246	0.352
Both eyes	0.028	0.052	0.068	0.063	0.085	0.024	-0.220	0.077	0.384	0.603	0.824

b)

Distractor condition	Distractor position (degrees)										
	-10	-8	-6	-4	-2	0	2	4	6	8	10
Dominant eye	-0.070	-0.039	-0.037	-0.060	-0.037	-0.053	-0.232	-0.232	-0.176	-0.068	-0.011
Non-dom eye	-0.016	-0.036	0.007	-0.021	-0.013	-0.019	-0.135	-0.149	-0.066	-0.022	0.046
Both eyes	-0.012	0.002	0.014	0.035	0.041	0.018	-0.382	-0.342	-0.169	-0.002	0.166

Table 5.7: Mean difference (pooled data for five subjects) in saccade gain with distractors at each eccentricity and without distractors for each distractor condition, a) 4° target presentation, b) 8° target presentation. Positive values represent an increase, and negative values a decrease, in gain with distractors compared to the no distractor condition.

When comparing monocular and binocular distractor conditions, a greater effect (decreased saccade accuracy) was demonstrated when the distractor was presented to both eyes in all subjects. From the pooled data for 4° targets (shown in Table 5.7a) gain decreased by 0.220 with the distractor at 2°, when the distractor was presented to both eyes simultaneously, by 0.128 when presented to the dominant eye and by 0.049 when presented to the non-dominant eye. Saccade gain increased by 0.824 with the distractor at 10° when the distractor was presented to both eyes simultaneously, by 0.240 when presented to the dominant eye and by 0.352 when presented to the non-dominant eye. For 8° target presentation (shown in Table 5.7b) gain decreased maximally by 0.382 with distractor at 2° when the distractor was presented to both eyes simultaneously, by 0.232 when presented to the dominant eye and by 0.135 when presented to the non-dominant eye.

Due to expected differences in the response for 4° and 8° target amplitudes (Walker, Deubel, Schneider & Findlay, 1997) statistical analysis was performed for each amplitude separately.

For Hypothesis 1, to show whether the effect on gain differed between contralateral and ipsilateral distractors and, for Hypotheses 3 and 5, to test for differences in saccade gain with distractors presented to the dominant, non-dominant and both eyes, a three-factor repeated measures ANOVA was performed. The three factors were; eye viewing the distractor (dominant, non-dominant or both eyes), side of distractor (contralateral or ipsilateral) and position of distractor (±2°, ±4°, ±6°, ±8° and ±10°).

For 4° targets this revealed a significant effect on which eye was viewing the distractor [$F(2,8)=13.688$, $p<0.01$]. There was a significant difference in the saccade gain between ipsilateral and contralateral distractors [$F(1,4)=48.635$, $p<0.01$] and distractor position [$F(4,16)=17.890$, $p<0.0001$]. All interactions were found to be significant with the highest p value being 0.0061. This showed that the effect of viewing eye depends on the side of the distractor with a significantly greater difference occurring for ipsilateral distractors. The effect of viewing eye on position of distractor is significantly greater with binocular distractors with the largest difference at 10°. The effect of position depends on side of distractor as there is no difference between position for contralateral distractors but there is a significantly different effect with position for ipsilateral distractors. From Figure 5.6, it would appear that the significant interactions related to the viewing eye resulted from the greater effect on gain with distractors to both eyes compared with the other two conditions.

To determine whether this was the case, the three-factor ANOVA was repeated with data from the both eyes condition removed to determine whether the significance disappeared. This was confirmed, as there were now no significant differences for eye viewing the distractor or any interactions between other factors and viewing eye. Details of the ANOVA are shown in Appendix 7.8.

For 8° targets this revealed no significant effect on which eye was viewing the distractor [$F(2,8)=2.572$, $p>0.05$]. There was a significant difference in the saccade gain between ipsilateral and contralateral distractors [$F(1,4)=24.230$, $p<0.01$] and distractor position [$F(4,16)=35.798$, $p<0.0001$]. All interactions were found to be significant with the highest p value being 0.0037 (see Appendix 7.9 for further details of the ANOVA) showing exactly the same pattern as described for 4° targets. From Figure 5.6 it would appear that this interaction results from the greater effect on gain with distractors to both eyes compared with the other two conditions.

To determine whether this was the case, the three-factor ANOVA was repeated with the both eyes condition removed. This revealed that there was now no significant difference in saccade gain with distractors to the dominant or non-dominant eye [$F(1,4)=4.157$, $p>0.05$], but there was a significant difference between the viewing eye and the side of the distractor [$F(1,4)=20.601$, $p<0.05$]. ANOVA details are shown in Appendix 7.10.

5.4 Discussion

The remote distractor effect was generated in the described laboratory set-up using a 1.5° distractor presented for 200ms simultaneously with the onset of the target. The results are discussed firstly with regard to the no distractor condition, followed by discussion relating to each of the hypotheses.

5.4.1 Saccades without distractors

In this present study, as shown in Table 5.3, the mean saccade latency with no distractors was 150ms (SD ±15.1), which was considerably lower than the typical values quoted in the literature as discussed in Chapter 4, Section 4.5.1. The results were consistent with the findings of Chapter 4 and Walker, Deubel, Schneider and Findlay (1997) using a similar paradigm, this was confirmed statistically, see Appendix 7.2.

Saccades were highly accurate for 4° targets in the no distractor condition, the mean gain for the group being 1.001 (SD ±0.045). For 8° targets, saccades were slightly hypometric, the mean gain being 0.971 (SD ±0.072). This decrease in accuracy for 8° targets was expected as the percentage of undershooting saccades increases, and overshooting saccades decreases, as the stimulus amplitude increases (Bartz, 1967; Becker, 1972). Kapoula and Robinson (1986) showed that the range of target positions used in an experimental session influences the accuracy of saccades, such that distances at the upper end of the range are underestimated, and those at the lower end of the range overestimated, regardless of the absolute amplitude.

A further reason for the slightly reduced gain may be expectational drift where a pre-saccadic movement of the eyes away from the fixation target occurs, decreasing the amplitude of the required saccade. In experimental paradigms with a known target direction expectational drift is frequently seen (Kowler and Steinman, 1979). However, saccades with obvious expectational drift were eliminated by the software or by visual inspection. Any small amounts existing in this current data would therefore be negligible.

5.4.2 The distractor effect with both eyes

Hypothesis 1: The reciprocal effect of distractors on saccade latency and gain, reported by Walker, Deubel, Schneider and Findlay (1997), will be replicated in our laboratory set-up when distractors are presented to both eyes.

From Table 5.4 the mean latency effect, with the distractor presented to both eyes at the original fixation point, produced an increase of 66ms for 4° targets and 59ms for 8° targets. This is greater than that shown by Walker, Deubel, Schneider and Findlay (1997) who found a 30ms to 40ms increase in a study of six normal subjects. This difference however was not found to be statistically different (see t test details in Appendix 7.2).

There are several reasons why these small differences may have occurred between the two studies; Walker, Deubel, Schneider and Findlay (1997) used a colour monitor to present stimuli, their target was 0.19° compared with 1° in this current study and they used distractors of 0.53° compared with 1.5° in this study. A pilot study revealed that the projection method with the use of the LCP shutters slightly reduced the target luminance; hence targets with a diameter of less than 1° were difficult to remain attentive to. Larger targets than those used by Walker, Deubel, Schneider and Findlay (1997) were therefore required to overcome this in the current study. As three distractor conditions were tested in this current study (dominant eye, non-dominant eye and both eyes) the number of saccades and the length of the study were greater than Walker, Deubel, Schneider and Findlay (1997) which could lead to differences in results.

With contralateral distractors an increase in latency of between 8ms and 26ms for 4° targets, and between 14ms and 29ms for 8° targets was found, as shown in Table 5.4. This is very similar to that shown by Walker, Deubel, Schneider and Findlay (1997) who reported increases of between 20ms and 30ms. The increase in saccade latency for contralateral distractors was found to be significantly larger than for ipsilateral distractors, and the change in latency at fixation was significantly different with distractors.

From Table 5.4 and Figure 5.5 it can be seen that distractors ipsilateral to the target from +4° to +10° had no effect on saccade latency. A small difference between this study and Walker, Deubel, Schneider and Findlay (1997) is evident for ipsilateral distractors at +2°. Walker, Deubel, Schneider and Findlay (1997) reported no increase

in latency in this position whilst the current study showed an increase in the region of 18ms. This may have been due to the larger distractor diameter used in the present study. Neurons within the rostral pole of the superior colliculus, which respond during active fixation, represent a central 2° area of the visual field (Munoz and Wurtz, 1992, 1993a, b). These cells were more likely to be stimulated with the 1.5° distractor used in the present study as the outer edge of the distractor was 1.25° from the original fixation point, approaching the 2° central area. This may have caused release of fixation to be more difficult, therefore increasing the saccade latency.

In this present study the effects on saccade gain were inverse to the effects observed on saccade latency as found in the results of Walker, Deubel, Schneider and Findlay (1997). Thus significant changes in gain were found for ipsilateral distractors whilst no effect was demonstrated for contralateral distractors. Ipsilateral distractors between fixation and the target reduced gain whilst distractors appearing beyond the target amplitude increased saccade gain. Specific values of the change in gain for saccades with distractors, were not given by Walker, Deubel, Schneider and Findlay (1997) however comparisons with their data can be made from Figure 5.1b, Figure 5.6 and Table 5.4. In the present study the maximum effect on gain for 4° targets, occurring with distractors at +10° eccentricity, were larger than the maximum effect for 8° targets, at +2° eccentricity, whilst Walker, Deubel, Schneider and Findlay (1997) found the opposite.

Small differences in the remote distractor effect on saccade latency and gain have been highlighted in the present study, compared to that of Walker, Deubel, Schneider and Findlay (1997). However, similar findings of a reciprocal effect of distractors on latency and gain, a maximum increase of latency at fixation, and equivalent increases in latency for contralateral distractors, have been demonstrated. It can be concluded that the effects were comparable between studies therefore Hypothesis 1 is supported.

5.4.3 The distractor effect in dominant and non-dominant eyes

Hypothesis 2: The effect of distractors on saccade latency when presented to the dominant eye will be significantly greater than when presented to the non-dominant eye.

As the dominant eye is thought to be more involved in visual direction and space localisation (Brod and Hamilton, 1971; Fowler and Stein, 1983), and as it activates a larger area of the primary visual cortex than the non-dominant eye (Rombouts, Barkhof,

Sprenger, Valk & Scheltens, 1996), the experiment tested whether distractors presented to the dominant eye would result in a greater effect on saccade latency and accuracy.

Figure 5.5 and Table 5.4 have shown that the difference in latency was small between dominant and non-dominant eye distractors. The maximum difference in latency between dominant and non-dominant eyes was 11ms for a 4° target with distractors at the original fixation point. Distractors to the dominant eye tended to give the largest increase, although this difference was negligible and not statistically significant, therefore Hypothesis 2 is rejected.

The eye movement data analysed in this current experiment was taken from the dominant eye. Hence distractors presented to the dominant or non-dominant eye affected saccades of the dominant eye equally. The findings of Zhou and King (1998) provide evidence that pre-motor neurons in the PPRF encode monocular commands for either right or left eye saccades, suggesting that organisation of the oculomotor system is monocular. They also found existence of binocular motor neurons indicating that convergence of pre-motor monocular signals may be crucial for binocular co-ordination. The results of the current study may suggest that sensory input to one eye has equal effects on both eyes. Analysis of saccades of each eye would be required to confirm this.

Hypothesis 3: The effect of distractors on saccade gain when presented to the dominant eye will be significantly greater than when presented to the non-dominant eye.

Figure 5.6 and Table 5.7 have shown that the difference in gain was small between dominant and non-dominant eye distractors. Distractors to the non-dominant eye tended to give the largest change in gain, although overall this difference was not statistically significant (see Section 5.3.2). The maximum difference in gain between dominant and non-dominant eyes was 0.112 for 4° targets with distractors at +10°, and 0.097 for 8° targets with distractors at +2°. For 4° targets the viewing eye was not significant whilst 8° targets did give a significant difference between the dominant and non-dominant eye depending on the side and position of the distractor.

An increased effect on gain, with ipsilateral distractors to the non-dominant eye, was found that was significantly different for 8° targets. Hypothesis 3 anticipated a greater effect of distractors in the dominant eye and was therefore rejected.

5.4.4 The distractor effect in monocular and binocular conditions

Hypothesis 4: The effect of distractors on saccade latency when presented binocularly will be greater than when presented monocularly.

The difference in effect on latency between monocular and binocular distractor conditions at fixation was small, with binocular distractors giving a slightly larger effect. Table 5.4 shows that this difference was maximum at fixation and amounted to 12.9ms for 4° targets and 11.7ms for 8° targets, which was not statistically significant. The significant results for differences in viewing eye, depending on the side of the distractor, was found to be due to the greater difference in the binocular condition compared to the monocular conditions. From Figure 5.5 and Table 5.2a it can be seen that this finding was not due to the greater contralateral effect binocularly compared to monocularly, but was due to the reduced (but still significant) difference between contralateral and ipsilateral distractors in the monocular conditions. In view of these contrasting results Hypothesis 4 could not be conclusively supported.

Why there was less difference between the effects of ipsilateral and contralateral distractors in the monocular conditions than in the binocular condition is not instantly clear. Walker et al (2000) found that temporal field (nasal retina) distractors had a greater effect on latency than nasal field distractors, possibly due to naso-temporal asymmetry in retinal ganglion cell density. This could have affected the results of the present study. As three of the five subjects were right eye dominant and two were left eye dominant, when distractors were presented to the dominant eye for rightward saccades the effect would have been greater for contralateral distractors for the right eye dominant subjects (distractor to temporal retina), but less in the left eye dominant subjects (distractor to nasal retinal). This could have reduced the overall effect of the side of the distractor. To determine whether this was the reason for the differences monocularly the experiment could be repeated with equal numbers of rightward and leftward saccades for dominant and non-dominant eye distractors eliminating the retinal side bias.

The effects of distractors at fixation on saccade latency have been attributed to an increase in activation of the fixation region of the SC, which is thought to inhibit triggering a saccade (Dorris and Munoz, 1995; Munoz and Wurtz, 1993a & b, 1995a & b). Walker, Deubel, Schneider and Findlay (1997) concluded that these inhibitory effects operate over a wider visual field as they found that distractors at any location in

the visual field, except a narrow sector around the target axis, affected saccade latency. Modification of this theory has been suggested (Olivier, Dorris & Munoz, 1999), due to findings reported by Krauzlis, Basso and Wurtz (1997), that the visual receptive fields of collicular fixation neurons are small and encompass only foveal and parafoveal regions of the contralateral visual field. Olivier, Dorris and Munoz (1999) proposed that the effect seen on latency may be due to a lateral inhibitory network within the intermediate layers of the SC. Presentation of a remote distractor would activate a second population of saccade-related neurons and lateral inhibitory interactions would therefore delay the motor command to initiate a saccade.

In the current study, the small trend for increased saccade latency for binocular distractor presentations, compared to monocular presentations at fixation (see Figure 5.5) and the larger contralateral to ipsilateral difference with binocular distractors (Appendix 7.4 and 7.5), may represent a slightly larger inhibitory effect in the intermediate layers of the SC in binocular distractor presentations. Further studies of collicular activity during binocular and monocular distractor presentations would be required to investigate this.

Hypothesis 5: The effect of distractors on saccade gain when presented binocularly will be greater than when presented monocularly.

Distractors appearing simultaneously to both eyes, gave rise to an increased effect on saccade gain compared to monocular distractor presentations (see Figure 5.6 and Table 5.7). In view of the results of this experiment being statistically significant, Hypothesis 5 is therefore supported.

The use of a flat projection screen means that distractors would not have stimulated directly corresponding points, however the disparity was small and did not give rise to diplopia of the distractor in any of the subjects at any eccentricity. Westendorf and Fox (1977) have shown that binocular summation is not restricted to excitation arising from stimuli registered in strict correspondence. They found binocular summation (summation in excess of probability summation) when flashes were presented to non-corresponding retinal points within a range of fusion.

This current study therefore demonstrates that binocular distractors create an enhanced effect, which reduces saccade gain more than monocular presentation. The experiment found that binocular summation of sensory input reduced motor performance.

The effect of distractors presented in the ipsilateral hemifield on saccade accuracy, where the saccade is directed to an intermediate position between the target and distractor (the global effect) has been attributed to collicular burst cells. It has been found that two stimuli, if closely located, can produce a single intermediate peak of activity (Glimcher & Sparks, 1993). Olivier, Dorris and Munoz (1999) suggested that lateral interaction within the intermediate layers of the SC may also explain this response. They proposed that presentation of a distractor in close proximity to the target would activate a second population of saccade-related neurons in overlapping receptive fields. Lateral excitatory interactions would therefore modify the motor command affecting the spatial saccade parameters.

This present study demonstrated a larger distractor effect on saccade gain for binocular compared to monocular distractor presentations. It may be speculated that distractor stimulation in both eyes activates a wider population of saccade-related neurons in overlapping receptive fields, than monocular distractor presentation, leading to greater modification of the motor command. Studies of activity in the intermediate layers of the SC with monocular and binocular distractors would be required to investigate this suggestion.

5.5 Conclusion

The distractor effect has been replicated for binocular distractors in subjects with normal bifoveal BSV. The effect is not notably different with distractors presented to either the dominant or non-dominant eye. For saccade gain a clear enhanced binocular response has been demonstrated in the remote distractor effect, such that distractors presented to both eyes have a greater effect on saccade gain than monocular presentations in the presence of normal bifoveal BSV. The effect of distractors on saccade latency was not different for monocular or binocular distractors at fixation but was significantly greater when considering the difference between contralateral and ipsilateral distractors.

The experiments in Chapter 6 will compare the effects described here in normal binocular subjects with the effect of monocular and binocular distractors in subjects with strabismus.

Chapter 6

The remote distractor effect in strabismus

This chapter presents the results of the distractor effect in strabismus and relates responses to binocular status. Eight subjects were studied and the results provide an insight into the programming of saccadic eye movements in the presence of strabismus with suppression (Experiment 5) and ARC (Experiment 8). Experiments to determine whether strabismic subjects with suppression were aware of the distractor presented within the suppression area are also included (Experiments 6 & 7).

6.1 Introduction

The previously documented binocular and monocular remote distractor effect in Experiment 4 of Chapter 5 will be used to answer two questions; firstly, in the presence of constant strabismus, does the deviating eye contribute to eye movement planning and, secondly, does this depend upon the subject's sensory status?

If the strabismic eye contributes to saccadic eye movement planning, distractors presented to the strabismic eye only should alter saccade latency and gain compared to the no distractor condition. As found in Experiment 4, an increased effect on saccade gain would also be expected with distractors presented to both eyes, compared to monocular presentation.

As described in Chapter 1, two adaptations may occur in strabismus to avoid diplopia and confusion, these are suppression and ARC. In the case of suppression, objects appearing within specific areas of the visual field of the deviating eye are not perceived. In the presence of ARC, abnormal BSV exists where the subject is aware of objects in the visual field of the deviating eye, but has a shift in retinal correspondence to compensate for the deviation.

The experiments presented in this chapter explored the effect of distractors presented monocularly and binocularly in subjects with strabismus and these two sensory adaptations. In view of the lack of perception of images within the suppression area it may be that visual information from these retinal areas does not contribute to eye movement planning. In ARC with the presence of anomalous BSV information from the deviating eye is perceived, distractors in the deviating eye should therefore affect

saccade latency and gain similarly to subjects with normal BSV as described in Chapter 5. However, changes in retinal localisation, to compensate for the angle of deviation and allow anomalous BSV, may also change localisation of the distractor effect. The maximum distractor effect may therefore still occur at the original fixation point, with distractor stimulating the pseudo-fovea. If re-mapping does not occur then the maximum effect may be when distractors are presented to the anatomical fovea, hence would be shifted from the original fixation point.

6.1.1 Experiment 5: The effect of distractors in strabismus with suppression

6.1.1.1 Hypotheses

For strabismic subjects with suppression and normal retinal correspondence:

1. a) Saccade latency will be affected by distractors presented binocularly and monocularly to the fixing eye. b) This effect will be equivalent to that demonstrated in normal BSV in Experiment 4. c) Saccade latency will be unaffected by distractors presented within the suppression area of the strabismic eye.
2. a) Saccade gain will be affected by distractors presented binocularly and monocularly to the fixing eye. b) The effect of distractors, presented to the fixing eye, will be equivalent to that demonstrated in the dominant eye of subjects with normal BSV in Experiment 4. c) Saccade gain will be unaffected by distractors presented within the suppression area of the strabismic eye. d) The enhanced effect of binocular distractors, as demonstrated in subjects with normal BSV in Experiment 4 will not be present.

6.2 Method

6.2.1 Participants

Six subjects with constant strabismus and suppression participated, three with esotropia and three with exotropia. Table 6.1 gives a summary of their clinical details. These subjects were previously described in Experiment 3, Chapter 4. Two subjects with constant strabismus, ARC and anomalous BSV were also investigated and are presented later in the chapter in Experiment 8. A clinical assessment of their visual function and strabismus was performed prior to Experiment 3 and full details of this are shown in Appendix 5 (subjects 1-6).

Subj	Age (years)	VA		Strabismus	PCT 1.14m (Δ)	Retinal corresp.	Suppression	Abnormal BSV		
		RE	LE					Sensory fusion	Motor fusion	SV
1	62.8	-0.1	0.2	left XT	2 BI	NRC	yes	no	no	no
2	22.8	0.0	-0.1	right ET	6 BO	NRC	yes	no	no	no
3	20.2	0.0	-0.1	right ET	6 BO	NRC	yes	no	no	no
4	41.0	-0.1	0.0	left XT	12 BI	NRC	yes	no	no	no
5	39.5	0.4	-0.1	right ET	12 BO	NRC	yes	no	no	no
6	19.4	-0.1	0.1	left XT	18 BI	NRC	yes	no	no	no

Table 6.1: Subject details - strabismic group with suppression. VA = logMAR visual acuity, RE = right eye, LE = left eye, ET = esotropia, XT = exotropia, BO = prism base out, BI = prism base in, SV = stereoscopic vision.

6.2.2 Apparatus

The equipment and stimuli were exactly as in Experiment 4 of Chapter 5.

6.2.3 Design of the experiment

The design was identical to Experiment 4, Chapter 5.

6.2.4 Procedure

Within one week of the clinical assessment and participating in Experiment 3 the participants attended three separate eye movement-recording sessions within a period of ten days.

The same procedure as described in Chapter 5 was repeated. The only difference in procedure was that the angle of deviation was measured before and immediately after the eye movement recording session using the prism cover test. This was to firstly assess whether the LCP shutters, running at 80Hz, affected the angle of strabismus and, secondly, to determine whether the angle of deviation changed following a 30 minute recording session. The fixation target used for the prism cover test measurements was a central 1° target cross, back projected on to the screen at a distance of 114cm, and the subjects were seated with head fixed in the chin and cheek head support, wearing the eye movement recorder head band. The LCP shutters were operating at 80Hz in the open position. The angle of strabismus was not affected by the dissociation of the shutters and did not change over the period of the testing session. These results are shown in Appendix 9.

6.3 Results

All six subjects with constant strabismus and suppression completed the experiment and were included in the analysis. All had dense suppression in the deviating eye (≥ filter 8 using the Bagolini filter bar) and large suppression areas extending beyond the distractor eccentricities presented in this study. A preliminary trial showed that whilst fixating the central fixation target presented to both eyes, all subjects were unaware of the presence of the distractor when presented monocularly to the strabismic eye at all eccentricities used, whereas when presented to the fixing eye or to both eyes they were visible (see later follow-up study, Experiment 6, Section 6.5). Data analysis followed the same sequence as in Experiment 4.

6.3.1 Saccade latency

Latency without distractors

The last column of Tables 6.2a and b shows the mean saccade latency for target presentations without distractors for each of the six subjects during each distractor test condition (i.e. during testing of distractors to fixing, strabismic and both eyes). Similar latencies occurred during all test conditions and both amplitudes, with the mean of the five subjects ranging from 158 ±15.5ms to 164 ±15.8ms for 4° targets and 165 ±10.9ms to 171 ±14.8ms for 8° targets. Subject 1 had longer latencies compared to the other subjects, having a mean of 189ms for all saccades without distractors.

To determine whether saccade latency was different during the three test conditions and for the two target amplitudes (4° and 8°), a two factor repeated measures ANOVA was performed. There was no significant difference in saccade latency for saccades without distractors in the three test conditions [$F(2,10)=3.146$, $p>0.05$], and no significant difference for the two saccade amplitudes [$F(1,5)=3.887$, $p>0.05$]. ANOVA details are shown in Appendix 10.1. The mean saccade latency without distractors for all test conditions was therefore pooled and is shown in Table 6.3.

Latency with distractors

Individual subject data of saccade latency in each distractor location for the three distractor conditions is shown in Table 6.2 a and b. Figure 6.1 shows the groups mean saccade latency plotted as a function of distractor eccentricity with distractors presented to both eyes, fixing eye and strabismic eye. Saccade latency without distractors is also shown for comparison.

Table 6.2a: The effect of distractors on saccade latency for 4 degree targets - pooled data for six subjects with suppression

Distractor fixing eye												
Distractor position	-10	-8	-6	-4	-2	0	2	4	6	8	10	no distractor
Subject 1	201.92	193.93	214.09	218.33	207.27	274.50	192.50	192.50	171.25	168.64	183.57	198.33
Subject 2	148.46	149.50	163.50	160.50	167.50	197.50	168.21	153.33	155.37	159.00	162.57	154.38
Subject 3	153.08	157.92	158.50	163.75	176.00	198.64	149.00	167.65	144.29	151.33	155.00	140.36
Subject 4	178.61	179.23	178.21	192.50	200.63	220.63	187.86	156.54	154.58	158.00	166.39	162.50
Subject 5	189.29	177.50	183.33	192.73	195.45	220.00	172.31	160.91	162.81	162.50	168.00	160.00
Subject 6	175.00	173.33	165.00	173.33	186.25	228.00	170.00	146.25	157.00	156.00	143.57	168.00
Mean	**174.39**	**171.90**	**177.11**	**183.52**	**188.85**	**223.21**	**173.31**	**162.86**	**157.55**	**159.24**	**163.18**	**163.93**
SD	**20.61**	**15.94**	**20.42**	**21.92**	**15.16**	**28.06**	**15.55**	**16.20**	**9.00**	**5.89**	**13.42**	**19.31**
SE	**8.42**	**6.51**	**8.34**	**8.95**	**6.19**	**11.45**	**6.35**	**6.61**	**3.68**	**2.41**	**5.48**	**7.88**
Distractor strabismic eye												
Distractor position	-10	-8	-6	-4	-2	0	2	4	6	8	10	no distractor
Subject 1	183.82	177.92	180.83	181.79	185.38	206.67	183.44	175.00	180.63	191.25	187.81	186.67
Subject 2	168.64	166.05	171.67	182.14	161.47	170.31	156.11	167.14	175.33	167.67	174.67	154.38
Subject 3	147.27	147.92	152.22	158.08	144.00	153.00	152.50	151.67	145.83	140.42	150.00	140.00
Subject 4	157.86	157.81	171.07	155.71	155.33	157.50	153.93	155.56	153.57	153.85	152.27	153.46
Subject 5	171.00	165.29	185.83	170.38	167.81	163.08	159.33	161.79	167.14	164.58	178.75	160.00
Subject 6	197.00	177.50	162.53	168.75	162.77	180.71	164.29	165.00	177.22	162.78	172.14	154.29
Mean	**170.93**	**165.42**	**170.69**	**169.48**	**162.80**	**171.88**	**161.60**	**162.69**	**166.62**	**163.42**	**169.27**	**158.13**
SD	**17.79**	**11.55**	**12.17**	**11.25**	**13.76**	**19.65**	**11.50**	**8.37**	**14.05**	**16.82**	**15.04**	**15.48**
SE	**7.26**	**4.71**	**4.97**	**4.59**	**5.62**	**8.02**	**4.69**	**3.42**	**5.74**	**6.87**	**6.14**	**6.32**
Distractor both eyes												
Distractor position	-10	-8	-6	-4	-2	0	2	4	6	8	10	no distractor
Subject 1	201.92	183.57	195.45	212.22	236.67	283.08	210.63	177.08	165.00	162.14	177.92	190.36
Subject 2	168.57	183.13	210.71	182.50	183.75	241.88	164.58	160.45	156.67	161.54	162.65	155.00
Subject 3	164.58	178.75	168.33	183.08	180.38	196.67	160.79	146.00	137.94	145.00	155.67	142.73
Subject 4	168.82	176.54	171.67	174.67	188.75	204.17	169.76	146.15	145.91	144.09	154.44	159.62
Subject 5	182.50	183.64	187.50	185.00	187.69	216.67	176.00	156.25	155.63	164.44	180.00	160.83
Subject 6	197.86	171.00	178.75	186.25	195.71	225.83	175.50	154.00	147.86	151.00	159.44	163.57
Mean	**180.71**	**179.44**	**185.40**	**187.29**	**195.49**	**228.05**	**176.21**	**156.66**	**151.50**	**154.70**	**165.02**	**162.05**
SD	**16.10**	**5.07**	**15.94**	**12.87**	**20.82**	**31.33**	**17.89**	**11.51**	**9.53**	**9.14**	**11.20**	**15.78**
SE	**6.57**	**2.07**	**6.51**	**5.25**	**8.50**	**12.79**	**7.30**	**4.70**	**3.89**	**3.73**	**4.57**	**6.44**

Table 6.2b: The effect of distractors on saccade latency for 8 degree targets - pooled data for six subjects with suppression

Distractor fixing eye												
Distractor position	-10	-8	-6	-4	-2	0	2	4	6	8	10	no distractor
Subject 1	190 94	222 69	221.94	232 27	253.18	281.15	205 00	197.69	180 00	180.42	194 23	189.45
Subject 2	163 46	171 58	174.17	174 67	184 58	208 06	158 33	181.79	163.33	150 00	147.50	155.33
Subject 3	164 38	166 67	166 56	177.50	188 89	182 00	165 33	160 00	143.75	139 29	148 33	153 00
Subject 4	200 83	188 44	200 38	199 58	220 63	231 92	180 63	160 29	163.75	157.81	155 42	176.47
Subject 5	193 46	193 85	197.00	195 56	198 00	206 67	191.50	185 91	185 00	164 58	202.50	183 08
Subject 6	185 00	172 86	184.17	175 00	202 50	205 00	190 71	176 82	156.11	158.11	159 00	168 00
Mean	183.01	186.01	190.70	192.43	207.96	219.13	181.92	177.08	165.32	158.37	167.83	170.89
SD	15.64	20.82	20.04	22.32	25.47	34.25	17.52	14.82	15.23	13.85	24.18	14.80
SE	6.39	8.50	8.18	9.11	10.40	13.98	7.15	6.05	6.22	5.65	9.87	6.04
Distractor strabismic eye												
Distractor position	-10	-8	-6	-4	-2	0	2	4	6	8	10	no distractor
Subject 1	180.33	174 64	183 67	187.86	173.75	200.67	177.78	188.18	171.00	186 67	189.50	183.57
Subject 2	180.71	179 17	187.25	209.12	207.50	180 83	171.39	170.29	161.15	163.33	175.56	169.00
Subject 3	152.25	142.73	163 93	151.67	153.18	146 67	136 25	155 00	153.46	140 26	147.50	152.81
Subject 4	169 64	168 64	179 67	178 21	172.73	162 86	163 75	156 88	154.29	156 00	161.54	157.50
Subject 5	178 89	172.33	183 44	172.50	188 57	167.22	166 25	168 89	165.91	172.00	181.33	168.18
Subject 6	171.67	148.75	161.00	181.25	172.86	160 63	153.33	157.22	146.67	160 00	162.50	161.23
Mean	172.25	164.38	176.49	180.10	178.10	169.81	161.46	166.08	158.75	163.04	169.65	165.38
SD	10.85	14.96	11.17	18.83	18.28	18.70	14.80	12.65	8.96	15.60	15.32	10.86
SE	4.43	6.11	4.56	7.69	7.46	7.63	6.04	5.16	3.66	6.37	6.25	4.43
Distractor both eyes												
Distractor position	-10	-8	-6	-4	-2	0	2	4	6	8	10	no distractor
Subject 1	206.88	191.47	230.94	216.76	235 00	256.33	220.45	179.17	196.67	186.47	176.00	186.56
Subject 2	156.67	164.64	170.00	167.00	186.67	214.12	185.00	187.14	158.06	150.00	160.67	162.00
Subject 3	158.18	167.31	161.11	167.50	168.46	198.57	156.25	146.67	147.06	143.61	161.92	155.00
Subject 4	176 67	180.88	182.00	183.46	198.46	207.06	186.88	154.71	157.94	147.94	155.00	161.76
Subject 5	197.08	190.67	200.00	200.38	192.50	195.00	173.13	166.00	156.36	176.54	177.50	173.75
Subject 6	172.50	182.50	183.00	182.50	195.00	217.22	185.00	172.00	155.00	153.00	150.00	157.22
Mean	178.00	179.58	187.84	186.27	196.01	214.72	184.45	167.61	161.85	159.59	163.51	166.05
SD	20.39	11.39	24.88	19.36	21.84	22.12	21.10	15.11	17.54	17.53	11.11	11.96
SE	8.32	4.65	10.16	7.91	8.92	9.03	8.61	6.17	7.16	7.16	4.54	4.88

Mean saccade latency with no distractor		
Subject	4° target	8° target
1	191.85	186.53
2	154.59	162.10
3	141.03	153.60
4	158.53	165.24
5	160.28	175.00
6	161.95	162.15
Mean	161.37	167.44
SD	16.72	11.61
SE	6.83	4.74

Table 6.3: Mean saccade latency without distractor presentation for each of the six subjects with strabismus and suppression. SD = standard deviation, SE = standard error.

Figure 6.1 and Table 6.2 a and b show that all subjects demonstrated a similar response with distractors presented to both eyes and to the dominant eye, which was also similar to the response found in Experiment 4 in subjects with normal BSV (see Figure 5.5). For both 4° and 8° targets latency was unaffected by distractors ipsilateral to the target but increased for contralateral distractors. The maximum increase in latency occurred with distractors at the original fixation point (distractor position zero). The effect of distractors presented to the strabismic eye is reduced compared to the other conditions. Latency is increased for 4° targets with contralateral distractors between -4° and -10°, at the original fixation point and very slightly for ipsilateral distractors at +10°. The mean increase for the group was small and similar in these positions, being approximately 10ms. For 8° targets latency increased for contralateral distractors between -2° and -6°. Similarly to 4° targets the increase was small with the maximum increase of almost 13ms with distractors at -4°.

Distractor at fixation

As in Experiment 4 the largest increase in latency for both eyes and fixing eye distractor conditions occurred at the original fixation point, represented as zero. For 4° targets the increase in saccade latency at the original fixation point was 66.7ms in the both eyes condition and 61.8ms in the fixing eye condition. For 8° targets the increase in latency with distractors at fixation was 47.3ms with distractors to both eyes and 51.7ms with distractors presented to the fixing eye.

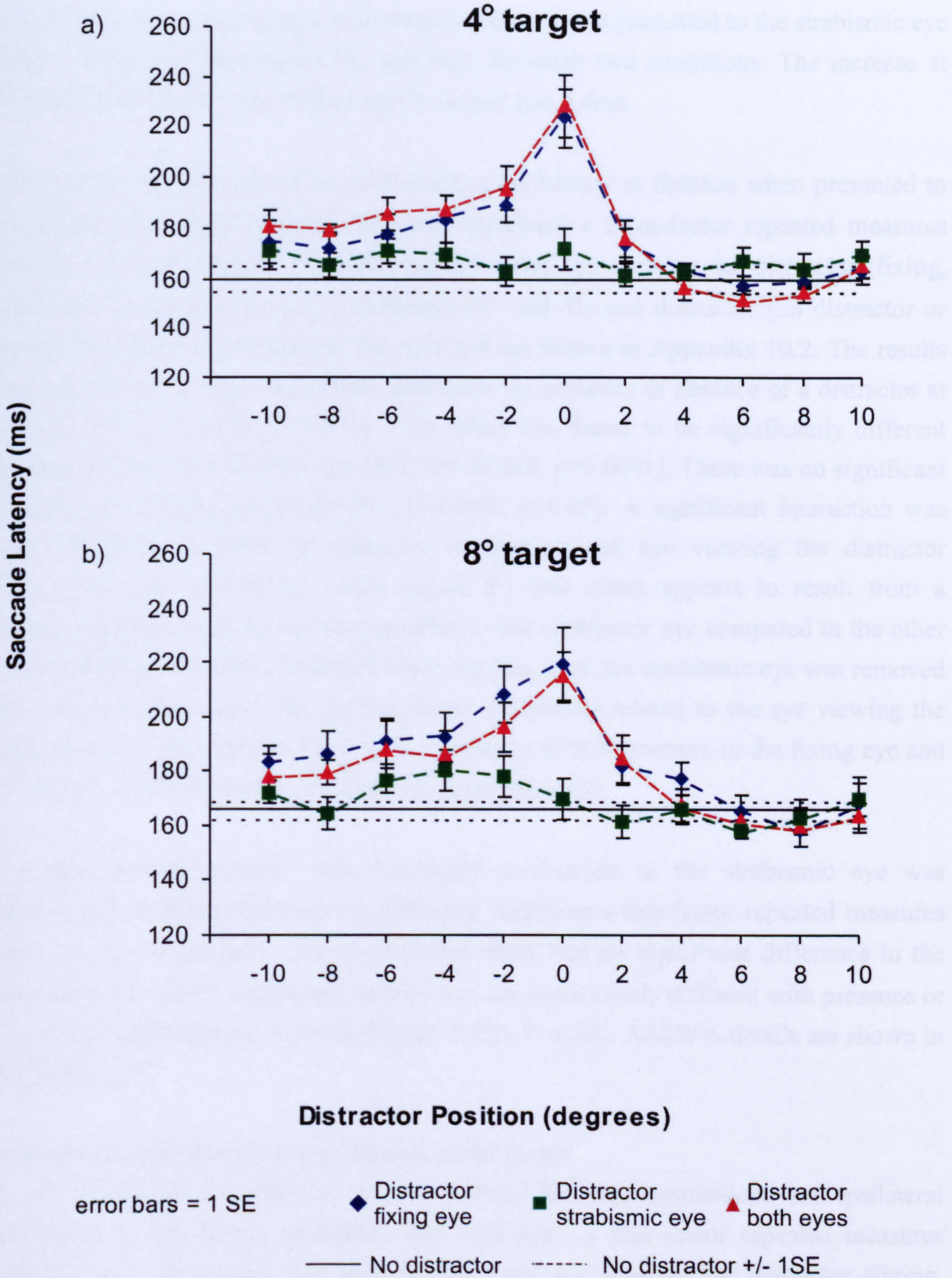


Figure 6.1: Effect of distractors on saccade latency, a) target presented at 4°, b) target presented at 8°. Pooled data for six subjects with constant strabismus and suppression.

From Figure 6.1 it can be seen that when the distractor is presented to the strabismic eye effects on latency are present but less than the other two conditions. The increase at fixation for 4° targets was 10.5ms and 8° targets just 2.4ms.

To establish whether the effect of distractors on latency at fixation when presented to the fixing, strabismic or both eyes was significant a three-factor repeated measures ANOVA was performed. The three factors were; eye viewing the distractor (fixing, strabismic or both eyes), target amplitude (4° and 8°) and distractor (no distractor or distractor at fixation). Details of the ANOVA are shown in Appendix 10.2. The results showed that there was a significant difference for presence or absence of a distractor at fixation [$F(1,5)=67.274$, $P<0.001$]. This effect was found to be significantly different for the three distractor conditions [$F(2,10)=49.064$, $p<0.0001$]. There was no significant difference for target amplitude [$F(1,5)=0.007$, $p>0.05$]. A significant interaction was found between presence of distractor at fixation and eye viewing the distractor [$F(2,10)=49.064$, $P<0.0001$]. From Figure 6.1 this effect appears to result from a smaller response with distractors presented to the strabismic eye compared to the other two conditions. This was confirmed when the data from the strabismic eye was removed from the ANOVA there was no significant differences related to the eye viewing the distractor, (i.e. the effect at fixation was the same with distractors in the fixing eye and both eyes). ANOVA details are shown in Appendix 10.3.

To show whether latency with distractors at fixation to the strabismic eye was significantly different from the no distractor condition a two-factor repeated measures ANOVA was performed. This showed that there was no significant difference in the response to 4° and 8° targets and latency was not significantly different with presence or absence of a distractor at fixation [$F(1,5)=3.586$, $P>0.05$]. ANOVA details are shown in Appendix 10.4.

Distractors contralateral and ipsilateral to the target

To show whether the effect on latency differed between contralateral and ipsilateral distractors to the fixing, strabismic and both eyes, a four-factor repeated measures ANOVA was performed. The four factors were; eye viewing the distractor (fixing, strabismic or both eyes), target amplitude (4° and 8°), side of distractor (contralateral or ipsilateral) and position of distractor (2°, 4°, 6°, 8° and 10°). ANOVA details are shown in Appendix 10.5. This revealed no significant effect for eye viewing the distractor [$F(2,10)=3.535$, $p>0.05$]. However, this did reveal a significant difference for target amplitude [$F(1,5)=11.317$, $p<0.05$] and for side of distractor [$F(1,5)=103.016$, $p<0.001$],

with contralateral distractors resulting in greater saccade latencies than ipsilateral distractors. Distractor position was also significant [$F(4,20)=12.289$, $p<0.0001$]. A significant interaction was found between eye viewing the distractor and side of distractor [$F(2,10)=8.045$, $p<0.01$], and an interaction between eye and distractor position [$F(8,40)=7.498$, $p<0.0001$]. From Figure 6.1 this difference appears to mainly result from the reduced response for distractors to the strabismic eye. This was confirmed by removal of the data of the strabismic eye from the analysis leaving no significant differences between the effect of distractors in the fixing eye and both eyes and no interactions between any of the factors relating to eye viewing the distractor; the results are shown in Appendix 10.6.

To determine whether the effect on latency differed between contralateral and ipsilateral distractors to the strabismic eye a three-factor repeated measures ANOVA was performed. This showed that there was no significant difference in the response for 4° and 8° targets. Latency was significantly different with distractors on the ipsilateral side compared to contralateral side when presented in the strabismic eye [$F(1,5)=9.703$, $p<0.05$] and significantly different depending on distractor position [$F(4,20)=3.134$, $p<0.05$]. From Figure 6.1 this appears to have resulted from the increased effect on latency for contralateral distractors between -2° and -6°. Details of the ANOVA are shown in Appendix 10.7.

The effects of distractors on latency in subjects with normal BSV reported in Experiment 4 were compared to the findings in strabismus with suppression. A summary of the effects in the two groups at the original fixation point is shown in Table 6.4.

To test whether there was a difference in the distractor effect at fixation in the two groups of subjects a series of three-factor mixed measures ANOVA's were performed for each distractor condition. The three factors were; group (BSV or strabismus with suppression), target amplitude (4° and 8°) and distractor at fixation (presence or absence).

Distractor condition	4° targets		8° targets	
	BSV group	Strabismic group	BSV group	Strabismic group
Dominant eye	53.0 ms	61.8 ms	47.5 ms	51.7 ms
Non-dom eye	41.5 ms	10.5 ms	44.2 ms	2.37 ms
Both eyes	65.9 ms	66.7 ms	59.2 ms	47.3 ms

Table 6.4: Change in saccade latency with distractors at fixation in subjects with normal BSV (n=5) and subjects with strabismus and suppression (n=6). The dominant eye represents the fixing eye in strabismus and the non-dominant eye represents the strabismic eye.

For distractors in the dominant (fixing) eye there was no significant difference between groups [$F(1,9)=2.141$, $p>0.05$], or target amplitude [$F(1,9)=0.043$, $p>0.05$]. The only significant effect was for presence or absence of a distractor [$F(1,9)=71.246$, $p<0.0001$]. There were no significant interactions between the factors indicating that for both 4° and 8° targets with distractors to the dominant eye, the distractor effect on latency was the same in both groups. ANOVA details are shown in Appendix 10.8.

For distractors in both eyes there was no significant difference between groups [$F(1,9)=1.047$, $p>0.05$], or amplitude [$F(1,9)=0.633$, $p>0.05$]. The only significant effect was for presence or absence of a distractor [$F(1,9)=144.796$, $p<0.0001$]. There were no significant interactions between the factors indicating that for both 4° and 8° targets with distractors to both eyes the distractor effect on latency was the same in both groups. ANOVA details are shown in Appendix 10.9.

For distractors in the non-dominant (strabismic) eye there was no significant difference between groups [$F(1,9)=0.125$, $p>0.05$], or target amplitude [$F(1,9)=0.258$, $p>0.05$]. There was a significant difference between presence or absence of a distractor [$F(1,9)=68.008$, $p<0.0001$] and a significant interaction between presence of a distractor and group [$F(1,9)=37.127$, $p<0.001$], showing that the effect on latency in strabismic subjects was significantly less than subjects with BSV (see Table 6.4). Details of the ANOVA are shown in Appendix 10.10.

To test whether there were differences for ipsilateral and contralateral distractors between the groups, a series of four-factor mixed measures ANOVA's were performed for each distractor condition. The four factors were; group (BSV or strabismus with suppression), target amplitude (4° and 8°), side of distractor (ipsilateral or contralateral) and position of distractor (2°, 4°, 6°, 8° and 10°).

For distractors in the dominant (fixing) eye there was no overall significant difference between groups [$F(1,9)=2.202$, $p>0.05$]. However, there was a significant interaction between side of distractor and group [$F(1,9)=10.616$, $p<0.01$]. From Figure 6.1 this shows that whilst both groups showed longer latencies for contralateral distractors than ipsilateral distractors the strabismic group had a larger difference between the two sides. ANOVA details are shown in Appendix 10.11.

For distractors in both eyes there was no significant difference between groups [$F(1,9)=2.266$, $p>0.05$]. There was a significant interaction between side of distractor

and group [$F(1,9)=13.875$, $p<0.01$], showing again that both groups showed longer latencies for contralateral distractors than ipsilateral distractors but the strabismic group had a larger difference between the two sides. ANOVA details are shown in Appendix 10.12.

For distractors in the non-dominant (strabismic) eye there was no significant difference between groups [$F(1,9)=0.490$, $p>0.05$]. There was a significant interaction between position of distractor and group [$F(4,36)=2.778$, $p<0.05$], indicating that both groups had a similar effect of increased contralateral effect compared to ipsilateral distractor effect. However, a difference between groups existed in the position of this effect. ANOVA details are shown in Appendix 10.13.

Individual Subject data

With distractors presented to the strabismic eye the lack of a clear peak latency increase may have been masked as the subjects had different angles of strabismus. Individual subject data was therefore plotted and is shown in Figures 6.2 and 6.3 for 4° and 8° targets respectively.

Subject 1 showed an increase in latency at the original fixation point only, for both 4° and 8° targets. Subject 2 had increased latency for contralateral distractors greater than ipsilateral distractors with maximum effect for distractors at -4°. Subject 3 had a maximum increase in latency with distractors on the contralateral side between -4° and -6°. Similarly subject 4 had an increase on the contralateral side, at -4° only for the 4° targets and with a maximum increase with distractors at -4° for 8° targets. For 4° targets subject 5 had an increase for contralateral distractors reaching a maximum at -6°, and for 8° targets increases in latency occurred at -6° and the original fixation point. Finally, subject 6 showed increased latency for various ipsilateral and contralateral positions for 4° targets, but had a maximum increase at -10° and for 8° targets increased latency occurs for contralateral distractors with a maximum effect at -4°. In all cases the maximum, or only, increase in latency occurred at a location stimulating the anatomical fovea (or within close proximity to it) of the deviating eye. A summary of this is shown in Table 6.5.

Subjects 1 and 2 showed an increased effect with binocular presentation compared with distractors to the fixing eye only. This difference is large for subject 2 but is only minimal for subject 1. This is reversed for subjects 4 and 5 who both showed a larger effect with distractors to the fixing eye only compared with the binocular stimulation.

The remaining two subjects had equal effects for fixing eye and binocular distractor presentations.

a) 4° target

Subject	Distractor at fixation in the strabismic eye (ms)	Maximum increase (ms)	Position of maximum increase	Expected location of anatomical fovea
1	25.30	25.30	0	-1
2	15.77	27.60	-4	-3
3	11.71	16.79	-4	-3
4	-0.92	12.65	-6	-6
5	1.56	24.32	-6	-6
6	19.40	37.41	-10	-9
Mean	**12.14**	**24.01**		
SD	**9.33**	**7.91**		
SE	**3.81**	**3.23**		

b) 8° target

Subject	Distractor at fixation in the strabismic eye (ms)	Maximum increase (ms)	Position of maximum increase	Expected location of anatomical fovea
1	21.43	21.43	0	-1
2	18.87	47.16	-4	-3
3	-6.84	10.42	-6	-3
4	-2.95	13.86	-6	-6
5	-1.78	19.57	-2	-6
6	-3.92	16.70	-4	-9
Mean	**4.14**	**21.52**		
SD	**12.54**	**13.16**		
SE	**5.12**	**5.37**		

Table 6.5: Difference in saccade latency with and without distractors presented to the strabismic eye for strabismic subjects with suppression. Positive values represent an increase and negative values a decrease in saccade latency with distractors. SD = standard deviation, SE = standard error.

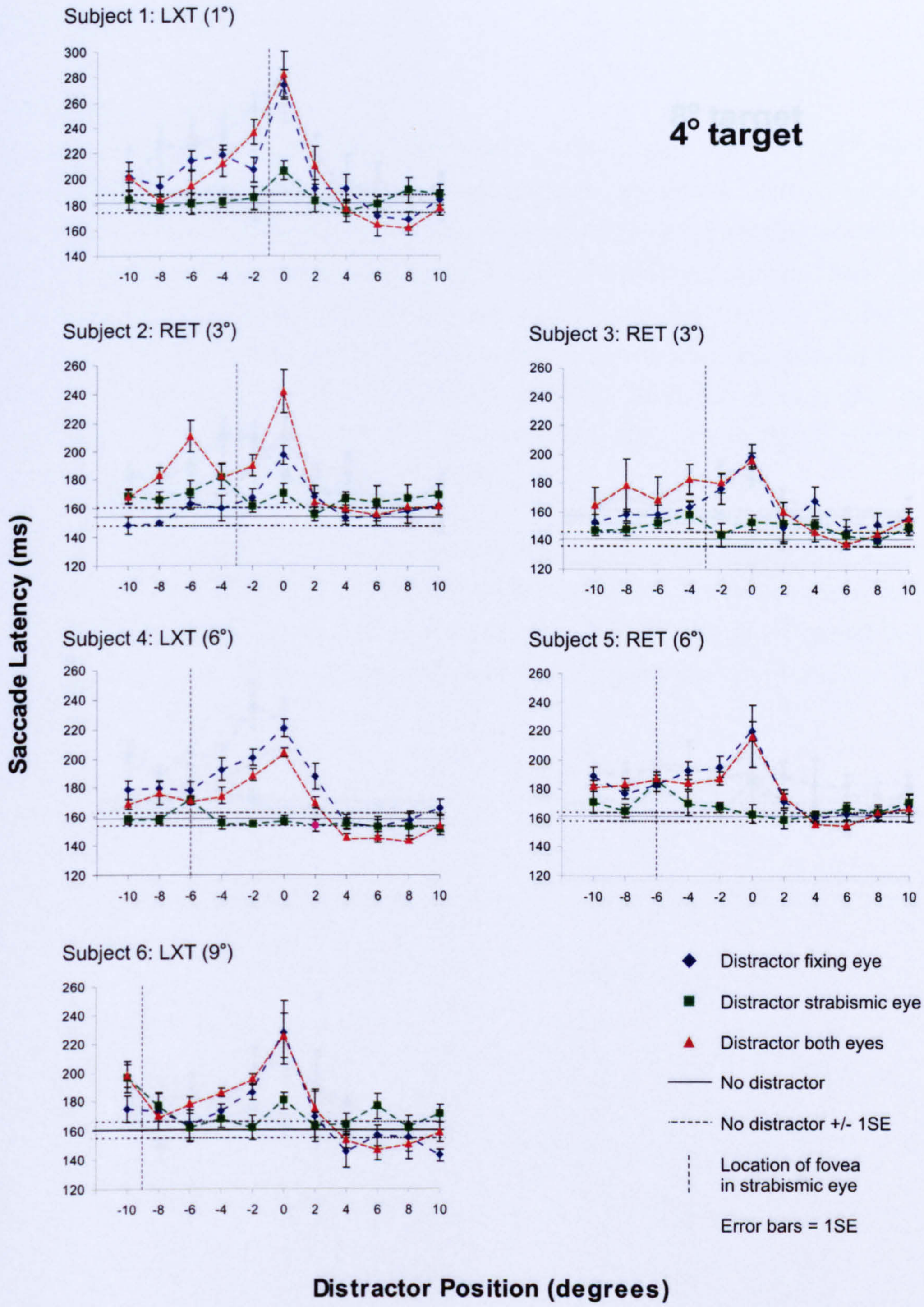


Figure 6.2: The effect of distractors presented simultaneously with a 4° target to the fixing eye, strabismic eye and both eyes, on saccade latency for six strabismic subjects with suppression. Zero distractor position represents the original central fixation point, negative values represent contralateral distractors and positive values represent ipsilateral distractors. The data for subject 1 is shown with a different axis range due to longer latencies than the other subjects. SE = standard error.

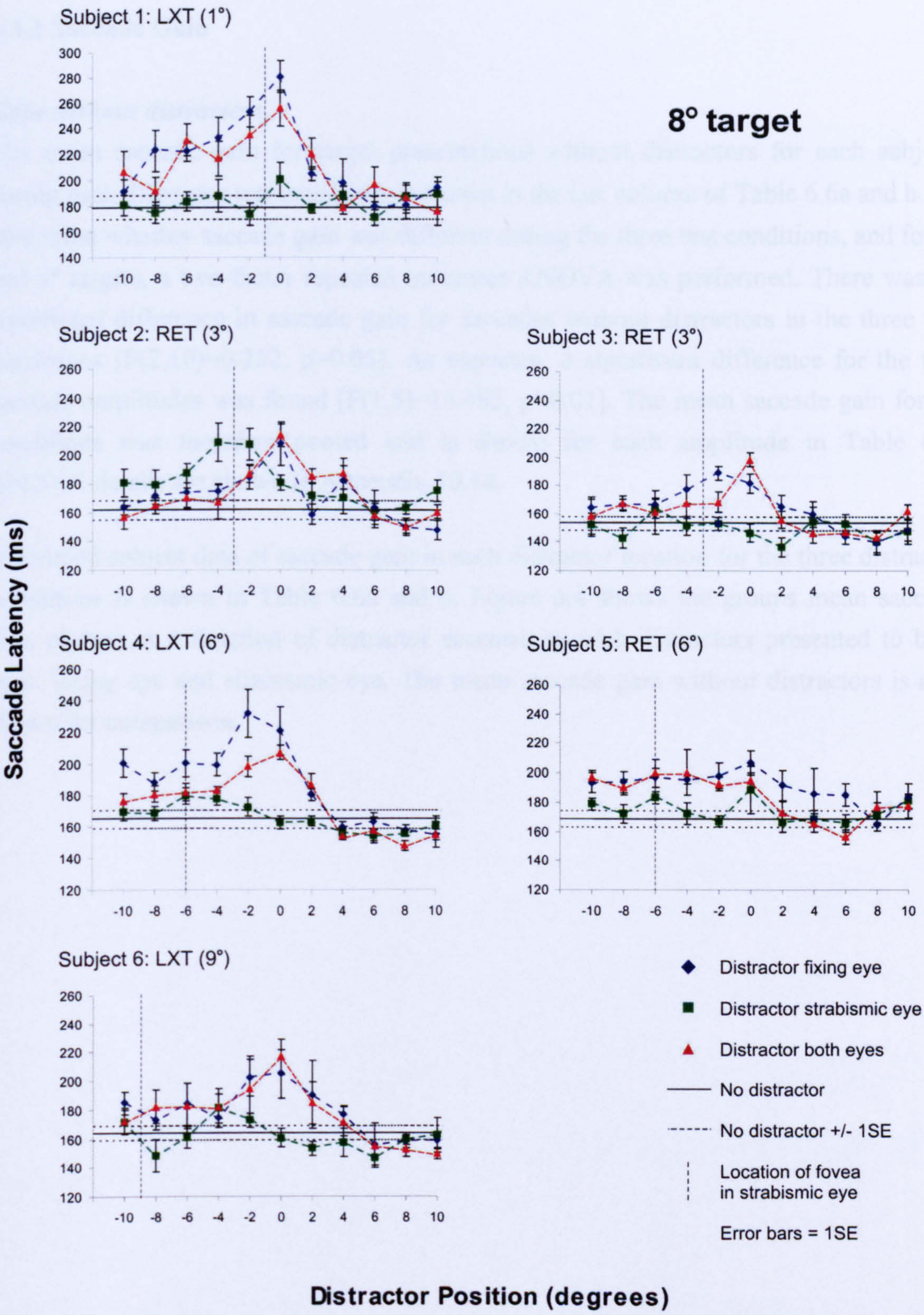


Figure 6.3: The effect of distractors presented to the fixing eye, strabismic eye and both eyes, (simultaneously with an 8° target), on saccade latency for six strabismic subjects with suppression. Zero distractor position represents the original central fixation point, negative values represent contralateral distractors and positive values represent ipsilateral distractors. The data for subject 1 is shown with a different axis range due to longer latencies than the other subjects. SE = standard error.

6.3.2 Saccade Gain

Gain without distractors

The mean saccade gain for target presentations without distractors for each subject, during each distractor test condition, is shown in the last column of Table 6.6a and b. To determine whether saccade gain was different during the three test conditions, and for 4° and 8° targets, a two-factor repeated measures ANOVA was performed. There was no significant difference in saccade gain for saccades without distractors in the three test conditions [$F(2,10)=0.232$, $p>0.05$]. As expected, a significant difference for the two saccade amplitudes was found [$F(1,5)=16.483$, $p<0.01$]. The mean saccade gain for all conditions was therefore pooled and is shown for each amplitude in Table 6.8. ANOVA details are shown in Appendix 10.14.

Individual subject data of saccade gain in each distractor location for the three distractor conditions is shown in Table 6.6a and b. Figure 6.4 shows the groups mean saccade gain plotted as a function of distractor eccentricity with distractors presented to both eyes, fixing eye and strabismic eye. The mean saccade gain without distractors is also shown for comparison.

Table 6.6a: The effect of distractors on saccade gain for 4 degree targets - pooled data for six subjects with suppression

Distractor fixing eye												
Distractor position	-10	-8	-6	-4	-2	0	2	4	6	8	10	no distractor
Subject 1	0.868	0.900	0.988	0.788	0.822	0.741	0.788	0.818	1.127	1.315	1.611	0.904
Subject 2	1.071	1.054	0.927	0.960	0.873	0.921	0.782	0.801	0.953	1.268	1.484	1.067
Subject 3	1.294	0.983	1.228	1.192	1.220	1.209	1.048	1.057	1.321	1.368	1.512	1.123
Subject 4	0.940	0.905	0.933	0.922	0.854	0.848	0.634	0.937	1.221	1.401	1.647	0.947
Subject 5	0.925	0.852	0.977	0.832	0.837	0.717	0.888	1.022	1.249	1.556	1.566	0.943
Subject 6	0.871	0.928	0.760	0.797	0.594	0.646	0.480	1.072	1.187	1.201	1.759	1.048
Mean	**0.995**	**0.937**	**0.969**	**0.915**	**0.867**	**0.847**	**0.770**	**0.951**	**1.176**	**1.352**	**1.596**	**1.005**
SD	**0.164**	**0.071**	**0.151**	**0.152**	**0.201**	**0.202**	**0.197**	**0.119**	**0.127**	**0.123**	**0.100**	**0.086**
SE	**0.067**	**0.029**	**0.062**	**0.062**	**0.082**	**0.083**	**0.080**	**0.049**	**0.052**	**0.050**	**0.041**	**0.035**
Distractor strabismic eye												
Distractor position	-10	-8	-6	-4	-2	0	2	4	6	8	10	no distractor
Subject 1	1.037	1.089	1.112	0.899	1.052	0.873	1.052	1.196	1.254	1.192	1.157	0.969
Subject 2	1.143	1.121	0.885	1.077	1.018	0.954	0.952	0.993	0.978	1.122	1.035	0.960
Subject 3	1.256	1.501	1.472	1.501	1.368	1.335	1.020	1.262	1.656	1.893	1.636	1.270
Subject 4	0.937	0.883	0.931	0.914	0.878	0.936	0.936	0.878	0.937	0.966	0.954	0.910
Subject 5	0.844	0.894	0.878	0.924	0.837	0.935	0.915	0.944	0.906	0.883	0.924	0.866
Subject 6	1.159	0.921	1.081	0.979	0.977	1.010	0.991	1.181	1.222	1.130	1.079	1.201
Mean	**1.063**	**1.068**	**1.060**	**1.049**	**1.022**	**1.007**	**0.978**	**1.076**	**1.159**	**1.198**	**1.131**	**1.029**
SD	**0.153**	**0.235**	**0.225**	**0.231**	**0.189**	**0.166**	**0.053**	**0.157**	**0.285**	**0.360**	**0.261**	**0.165**
SE	**0.063**	**0.096**	**0.092**	**0.094**	**0.077**	**0.068**	**0.021**	**0.064**	**0.116**	**0.147**	**0.107**	**0.068**
Distractor both eyes												
Distractor position	-10	-8	-6	-4	-2	0	2	4	6	8	10	no distractor
Subject 1	1.013	1.034	1.024	1.032	0.912	1.017	0.827	0.935	1.491	1.517	1.599	0.950
Subject 2	0.954	0.840	0.815	0.851	0.979	0.767	0.715	0.828	1.135	1.334	1.453	0.965
Subject 3	1.219	1.122	1.196	1.176	1.209	1.228	1.097	1.483	1.732	1.831	2.154	1.257
Subject 4	0.930	0.969	0.948	0.942	0.905	0.953	0.712	0.987	1.307	1.401	1.721	0.996
Subject 5	0.901	0.887	0.922	0.927	0.943	0.948	0.861	0.979	1.287	1.579	1.419	0.908
Subject 6	1.195	1.001	1.082	1.071	1.086	0.892	0.779	0.918	1.345	1.985	2.339	0.848
Mean	**1.035**	**0.975**	**0.998**	**1.000**	**1.006**	**0.968**	**0.832**	**1.021**	**1.383**	**1.608**	**1.781**	**0.987**
SD	**0.138**	**0.102**	**0.133**	**0.117**	**0.119**	**0.153**	**0.143**	**0.233**	**0.206**	**0.253**	**0.381**	**0.142**
SE	**0.056**	**0.042**	**0.054**	**0.048**	**0.049**	**0.062**	**0.058**	**0.095**	**0.084**	**0.103**	**0.156**	**0.058**

Table 6.6b: The effect of distractors on saccade gain for 8 degree saccades - pooled data for 6 subjects with suppression

Distractor fixing eye												
Distractor position	-10	-8	-6	-4	-2	0	2	4	6	8	10	no distractor
Subject 1	0.738	0.789	0.820	0.764	0.820	0.831	0.625	0.483	0.698	0.617	0.747	0.798
Subject 2	0.892	0.748	0.862	0.869	0.775	0.912	0.540	0.568	0.586	0.871	1.062	0.968
Subject 3	1.006	0.842	0.960	0.850	1.067	0.796	0.727	0.820	0.991	1.101	1.094	0.824
Subject 4	0.858	0.871	0.868	0.853	0.858	0.792	0.420	0.447	0.684	0.790	0.928	0.866
Subject 5	0.852	0.907	0.881	0.887	1.001	0.949	0.564	0.607	0.519	0.792	0.779	0.835
Subject 6	0.877	0.846	0.766	0.838	0.707	0.783	0.597	0.551	0.530	0.702	0.964	0.799
Mean	**0.870**	**0.834**	**0.859**	**0.843**	**0.871**	**0.844**	**0.579**	**0.579**	**0.668**	**0.812**	**0.929**	**0.848**
SD	**0.086**	**0.057**	**0.065**	**0.042**	**0.137**	**0.070**	**0.102**	**0.131**	**0.175**	**0.166**	**0.143**	**0.064**
SE	**0.035**	**0.023**	**0.026**	**0.017**	**0.056**	**0.029**	**0.041**	**0.054**	**0.072**	**0.068**	**0.058**	**0.026**
Distractor strabismic eye												
Distractor position	-10	-8	-6	-4	-2	0	2	4	6	8	10	no distractor
Subject 1	0.763	0.899	0.806	0.807	0.795	0.839	0.830	0.723	0.856	0.716	0.787	0.896
Subject 2	1.045	1.174	0.912	0.831	1.058	0.821	0.999	0.867	1.066	1.097	1.002	0.971
Subject 3	0.950	1.120	1.156	1.147	1.019	0.901	1.144	0.915	0.990	0.989	0.900	0.881
Subject 4	0.851	0.837	0.848	0.897	0.836	0.819	0.829	0.836	0.828	0.824	0.832	0.872
Subject 5	0.876	0.759	0.818	0.790	0.808	0.855	0.844	0.741	0.801	0.781	0.777	0.749
Subject 6	0.902	0.950	0.795	0.996	0.980	0.859	0.813	0.876	0.847	0.861	0.987	0.866
Mean	**0.898**	**0.956**	**0.889**	**0.911**	**0.916**	**0.849**	**0.910**	**0.826**	**0.898**	**0.878**	**0.881**	**0.872**
SD	**0.095**	**0.162**	**0.137**	**0.138**	**0.116**	**0.030**	**0.134**	**0.077**	**0.105**	**0.141**	**0.098**	**0.072**
SE	**0.039**	**0.066**	**0.056**	**0.056**	**0.048**	**0.012**	**0.055**	**0.032**	**0.043**	**0.058**	**0.040**	**0.029**
Distractor both eyes												
Distractor position	-10	-8	-6	-4	-2	0	2	4	6	8	10	no distractor
Subject 1	0.853	0.827	0.822	0.832	0.815	0.834	0.470	0.516	0.722	0.841	0.921	0.839
Subject 2	0.809	0.827	0.792	0.919	0.763	0.755	0.531	0.465	0.532	0.721	0.922	0.869
Subject 3	0.971	0.960	1.100	1.033	1.053	1.035	0.861	0.874	0.914	1.048	1.042	1.077
Subject 4	0.923	0.885	0.928	0.855	0.904	0.861	0.783	0.472	0.687	0.809	0.946	0.833
Subject 5	0.867	0.747	0.838	0.852	0.892	0.847	0.659	0.564	0.712	0.808	0.875	0.789
Subject 6	0.930	0.992	0.938	0.934	0.988	1.037	0.644	0.690	0.797	1.017	1.098	0.970
Mean	**0.892**	**0.873**	**0.903**	**0.904**	**0.902**	**0.895**	**0.658**	**0.597**	**0.728**	**0.874**	**0.967**	**0.896**
SD	**0.059**	**0.092**	**0.113**	**0.075**	**0.107**	**0.115**	**0.147**	**0.159**	**0.126**	**0.129**	**0.085**	**0.107**
SE	**0.024**	**0.037**	**0.046**	**0.031**	**0.044**	**0.047**	**0.060**	**0.065**	**0.052**	**0.053**	**0.035**	**0.044**

Mean saccade gain with no distractor		
Subject	**4° target**	**8° target**
1	0.976 SD 0.176	0.871 SD 0.203
2	0.985 SD 0.233	0.937 SD 0.281
3	1.243 SD 0.165	0.910 SD 0.203
4	0.951 SD 0.109	0.892 SD 0.137
5	0.902 SD 0.218	0.794 SD 0.187
6	1.010 SD 0.236	0.894 SD 0.185
Mean **SD** **SE**	**1.011** **0.119** **0.049**	**0.883** **0.049** **0.020**

Table 6.7: Mean saccade gain without distractors for individual subjects with strabismus and suppression. SD = standard deviation, SE = standard error.

All subjects demonstrated a typical distractor effect with distractors to both eyes and fixing eye. For 4° targets a clear decrease in gain occurred for ipsilateral distractors at +2° and an increase in gain occurred with distractors beyond the target from +6° to +10° when distractors were presented to both eyes and fixing eye only. The largest increase in gain for both conditions occurred with distractors at +10°. The increase in saccade gain at this position was 0.770 in the both eyes condition and 0.587 in the fixing eye condition, showing a small enhanced binocular response. For 8° targets a large decrease in gain occurred for ipsilateral distractors presented between the original fixation point and the target (+2° to +6°) the maximum decrease in gain was 0.286 with distractors to both eyes, and 0.304 with distractors to the fixing eye.

Four of the six subjects showed small alterations to saccade gain when distractors were presented to the strabismic eye. From Figure 6.4 it can be seen that, when the distractor was presented to the strabismic eye, effects on gain were small for 4° targets. The maximum increase in gain occurred at +8° where an increase in gain of 0.187 was present. There was a minimal effect at +4° for 8° targets.

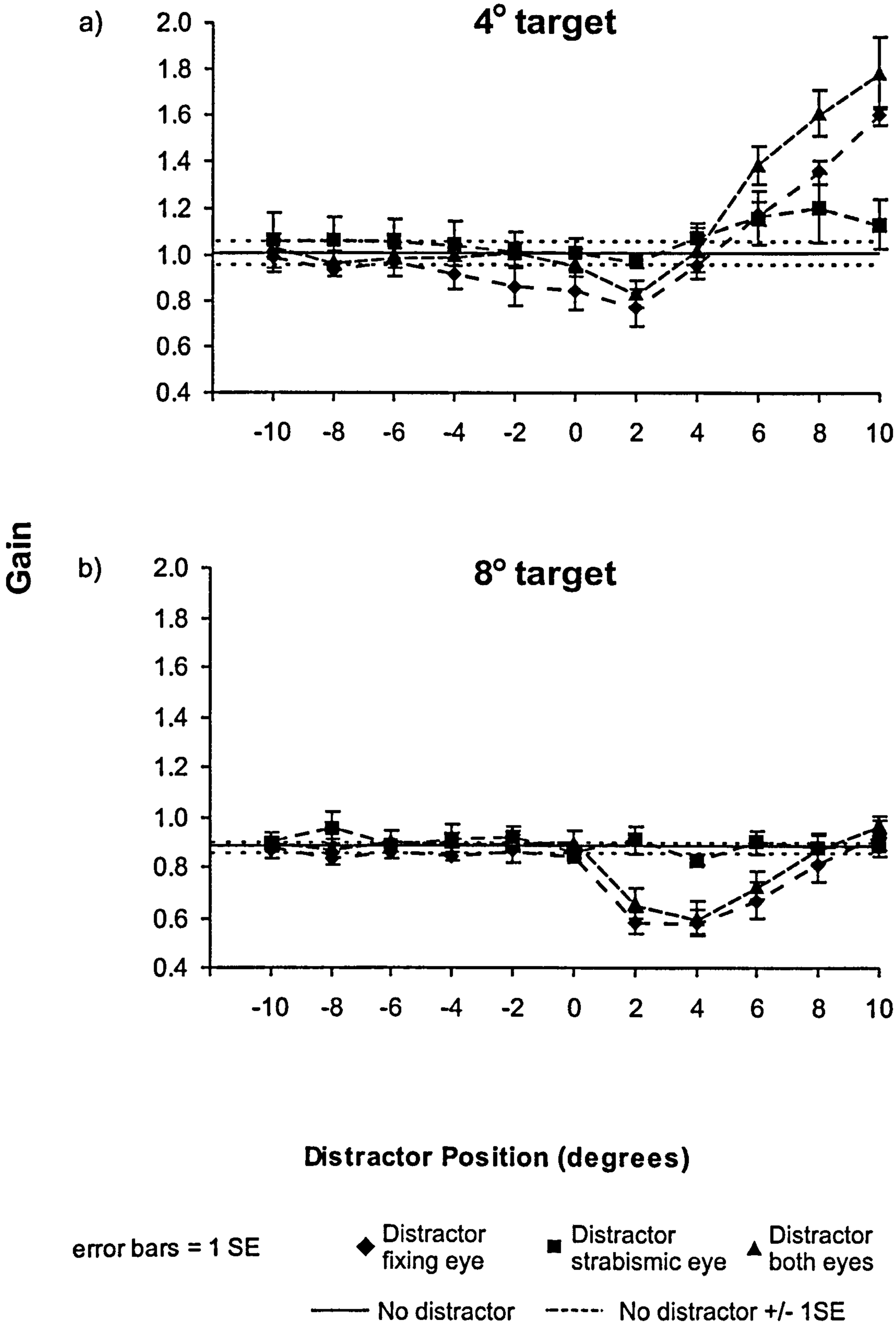


Figure 6.4: Effect of distractors on saccade gain, a) target presented at 4°, b) target presented at 8°. Pooled data for six subjects with constant strabismus and suppression.

To show whether the effect on gain differed between contralateral and ipsilateral distractors and, to the fixing, strabismic and both eyes, a three-factor repeated measures ANOVA was performed for each target amplitude. The three factors were; eye viewing the distractor (fixing, strabismic or both eyes), side of distractor (contralateral or ipsilateral) and position of distractor (2°, 4°, 6°, 8° and 10°). ANOVA details are shown in Appendices 10.15 and 10.16. This showed a significant difference in gain for side of distractor at 4° [$F(1,5)=24.116$, $p<0.01$] and between distractor position for 4° targets [$F(4,20)=3.214$, $p<0.05$] and 8° targets [$F(4,20)=13.184$, $p<0.0001$]. No significant effect was found for eye viewing the distractor for 8° targets [$F(2,10)=0.829$, $p>0.05$] but this was significant for 4° targets [$F(2,10)=4.311$, $p<0.05$]. This effect occurred as gain reduced slightly for contralateral distractors between -4° and the original fixation point in the fixing eye only. A significant interaction was found between eye viewing the distractor, side of distractor and position of distractor for both 4° [$F(8,40)=38.311$, $p<0.0001$], and 8° targets [$F(8,40)=9.449$, $p<0.0001$]. From Figure 6.4 it appears that this difference resulted from the reduced response for distractors to the strabismic eye. When the data from the strabismic eye was removed from the ANOVA there was no significant difference in the effect on gain between the fixing eye and both eyes conditions and no significant interactions between the eye viewing distractor and other factors. ANOVA details are shown in Appendices 10.17 and 10.18. This indicates that the differences found in the distractor effect on gain related to viewing eye resulted from the reduced response when distractors are presented to the strabismic eye only.

To determine whether the effect on gain differed between contralateral and ipsilateral distractors to the strabismic eye a two-factor repeated measures ANOVA was performed. ANOVA details are shown in Appendices 10.19 and 10.20. For 4° targets this showed no significant difference for side [$F(1,5)=5.525$, $p>0.05$] or position [$F(4,20)=2.310$, $p>0.05$] and no significant interactions between the factors. For 8° targets there was a significant difference in gain with side of distractor [$F(1,5)=7.625$, $p<0.05$] but no significant effect for position of distractor or any interactions between these factors.

The effects of distractors on gain in subjects with normal BSV reported in Experiment 4 were compared to the findings in strabismus with suppression. A summary of the maximum effects on gain in the two groups is shown in Table 6.8.

Distractor	4° targets		8° targets	
	BSV	Strabismus & suppression	BSV	Strabismus & suppression
Dominant eye	0.240	0.587	0.232	0.304
Non-dominant eye	0.352	0.187	0.135	0.057
Both eyes	0.824	0.770	0.382	0.286
Enhanced binocular effect	**0.472**	**0.183**	**0.150**	**-0.018**

Table 6.8: Summary of maximum change in saccade gain with distractors for the two subject groups. Group mean data for five subjects with BSV (reported in Experiment 4) and six subjects with manifest strabismus and suppression. The enhanced binocular effect is the change in gain for distractors to both eyes minus change in gain for distractors presented monocularly. Monocular values are taken as the eye with maximum change in gain.

To test for differences in gain for ipsilateral and contralateral distractors between the groups, a series of three-factor mixed measures ANOVA's was performed for each target amplitude and distractor condition. The three factors were; group (BSV or strabismus with suppression), side of distractor (ipsilateral or contralateral) and position of distractor (2°, 4°, 6°, 8° and 10°). ANOVA details are shown in Appendices 10.21 to 10.26.

For distractors in the dominant (fixing) eye there was no significant difference between groups; for 4° targets [$F(1,9)=0.001$, $p>0.05$] or for 8° targets [$F(1,9)=5.048$, $p>0.05$]. For 4° targets there was a significant interaction between side, position and group [$F(4,36)=3.056$, $p<0.05$]. For 8° targets there were no significant interactions. From Figures 5.6 and 6.4 the significant difference for 4° targets was a larger effect at +8° and +10° in the fixing eye of strabismic subjects than the dominant eye of the BSV subjects.

For distractors in both eyes there was no significant difference between groups; for 4° targets [$F(1,9)=0.168$, $p>0.05$] or for 8° targets [$F(1,9)=2.692$, $p>0.05$]. The only significant interaction related to group was for 8° targets, between side, position and group [$F(4,36)=5.544$, $p<0.01$]. From Figures 5.6 and 6.4 it appears that this difference results from a slightly smaller increase in gain for 10° distractors in the strabismic group, which is not the position of main effect with 8° targets.

For distractors in the non-dominant (strabismic) eye there was no significant overall difference between groups; for 4° targets [$F(1,9)=0.040$, $p>0.05$] or for 8° targets [$F(1,9)=0.515$, $p>0.05$]. The only significant interaction related to group was between side, position and group for 8° targets: [$F(4,36)=3.081$, $p<0.05$], showing that the effect on gain in the strabismic group was significantly less than in the BSV group. Whilst for

4° targets the effect in the strabismic group was less than the BSV group it was not significantly different.

Individual subject data

To identify any individual patterns individual subject data was plotted and is shown in Figures 6.5 and 6.6 for 4° and 8° targets respectively. Subjects 4 and 5 showed no effect on saccade gain with distractors presented to the strabismic eye. Subject 3 demonstrated a normal effect for ipsilateral distractors but also increased gain for contralateral distractors. For 4° targets subjects 1 and 6 showed a small increase in saccade gain with ipsilateral distractors, but atypically the increase began with distractors at +4° (the target amplitude) and peaked with distractors at +6°. Subject 2 revealed a variable effect with very slightly increased and decreased gains for ipsilateral and contralateral distractors, but with no clear pattern.

Overall, the effects on saccade gain from the strabismic eye were present but small with 2 subjects having no effect. Two of the six subjects demonstrated larger effects on gain with distractors presented to both eyes compared to distractors presented to the fixing eye only.

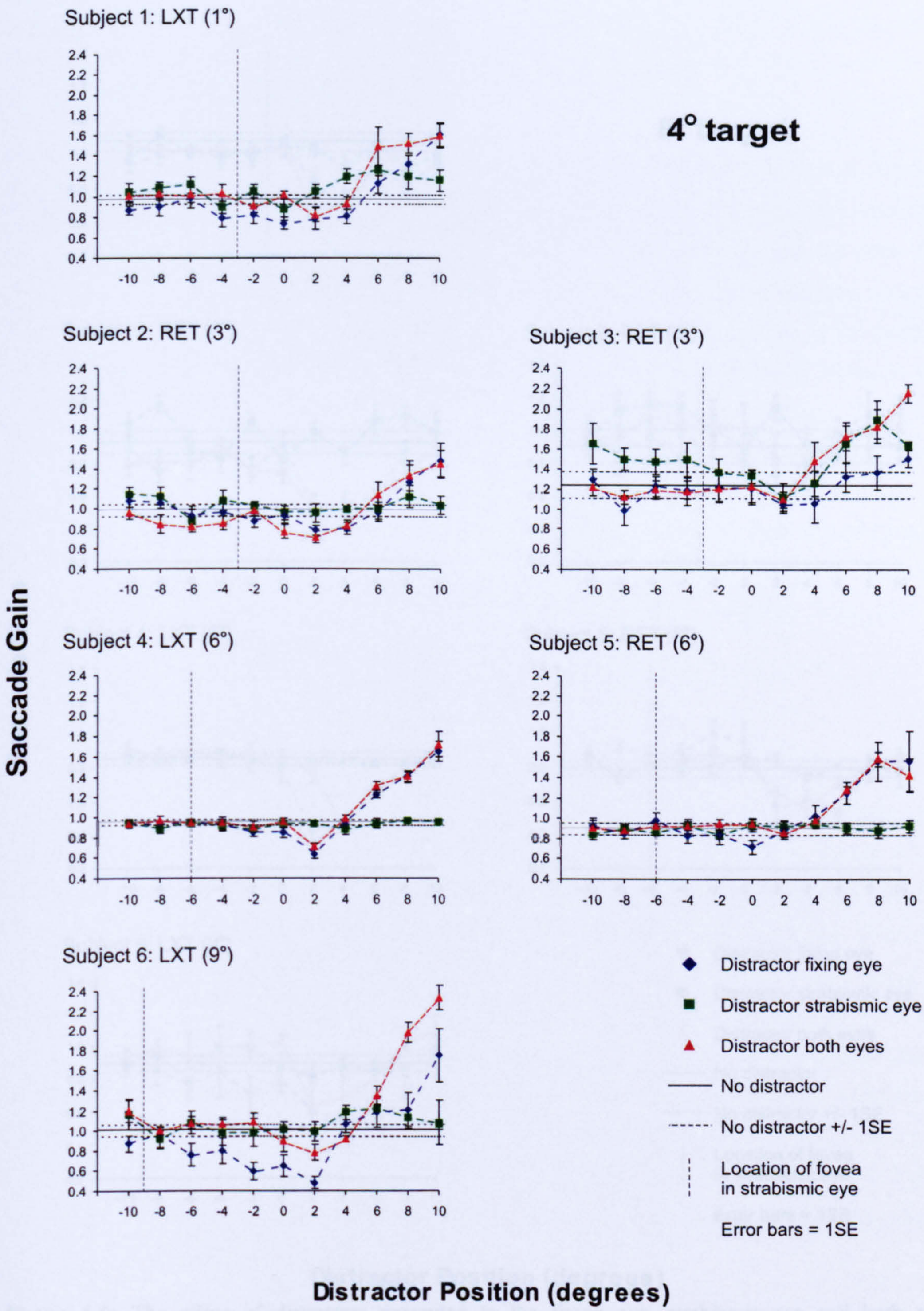


Figure 6.5: The effect of distractors presented to the fixing eye, strabismic eye and both eyes, (simultaneously with a 4° target), on saccade gain for six strabismic subjects with suppression. Zero distractor position represents the original central fixation point, negative values represent contralateral distractors and positive values represent ipsilateral distractors. ET = esotropia, XT = exotropia, SE = standard error.

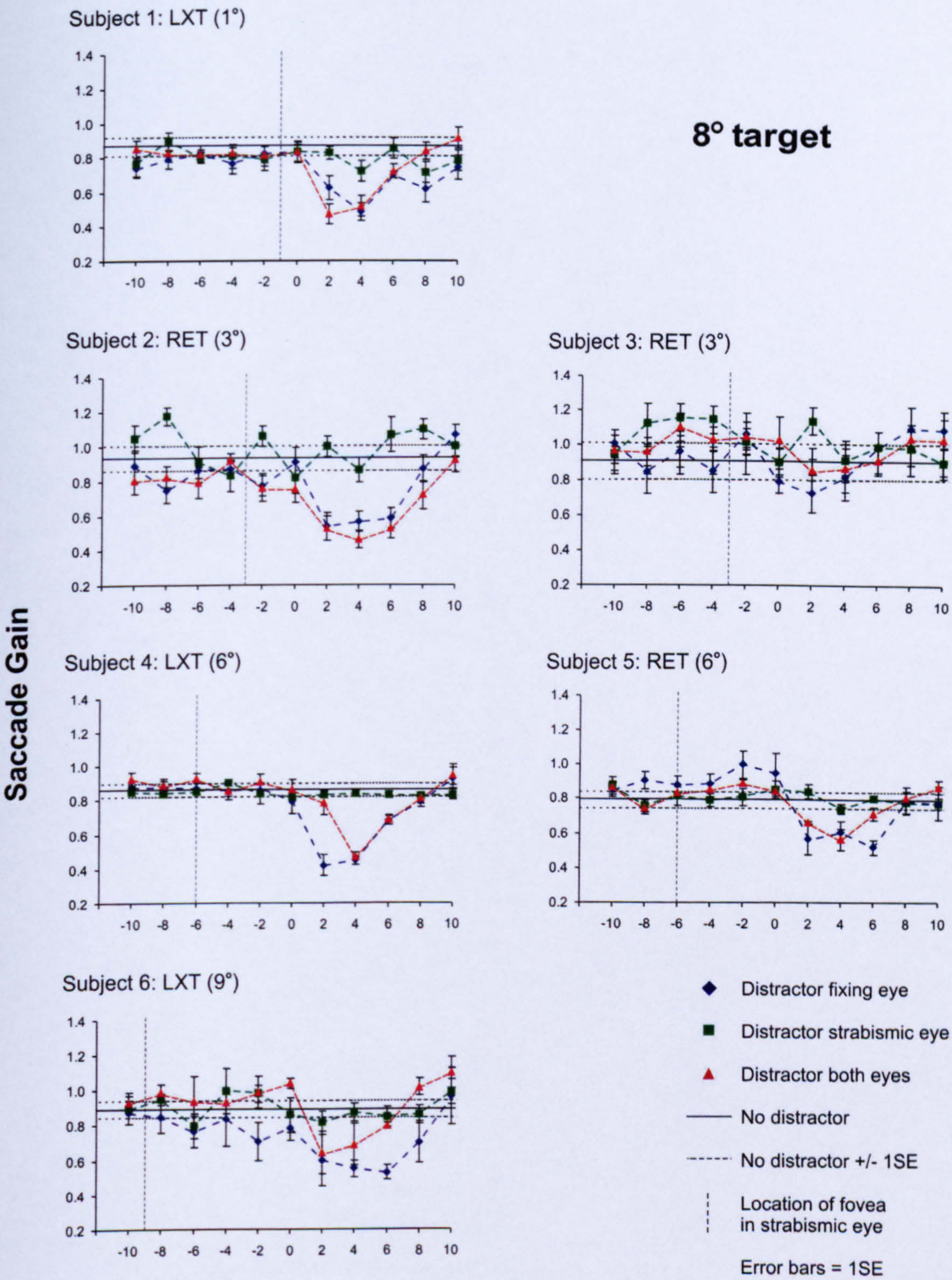


Figure 6.6: The effect of distractors presented to the fixing eye, strabismic eye and both eyes, (simultaneously with an 8° target), on saccade gain for six strabismic subjects with suppression. Zero distractor position represents the original central fixation point, negative values represent contralateral distractors and positive values represent ipsilateral distractors. ET = esotropia, XT = exotropia, SE = standard error.

6.4 Discussion

6.4.1 Saccades without distractors

The mean saccadic latency for the group of six strabismic subjects in the no distractor condition (Table 6.3) was slightly higher than that found under the same test conditions in the subjects with normal BSV in Experiment 4 (Table 5.3). It can be seen from individual subject mean data that some subjects demonstrated short latency saccades, which resulted in low gain saccades with large standard deviations. This is the probable result of a predictable saccade task of 30 minutes duration in which the subjects were aware of the saccade direction prior to commencing the experiment. The target amplitude was not entirely predictable as two amplitudes were randomly used. Bronstein and Kennard (1997) have reported the phenomenon of short latency low gain saccades in predictable tasks. It was necessary to use a known non-randomised direction to avoid any increase in latency on distractor trials caused by the additional discrimination process required to select the target (Walker, Deubel, Schneider and Findlay, 1997).

6.4.2 Saccade latency

Hypothesis 1a postulated that distractors presented binocularly and monocularly to the fixing eye would affect saccade latency. This was supported as shown in Figure 6.1 and statistically (Appendices 10.3 and 10.6). The experiment revealed significant increases in saccade latency for distractors at the original fixation point and for distractors contralateral to the target. The effects in the fixing eye and both eyes were compared with the response in subjects with normal BSV from the dominant eye and both eyes. Figures 5.5 and 6.1 and statistical analysis (Appendices 10.8 & 10.9) showed that the effect at fixation was the same in both groups and both had longer latencies for contralateral distractors with no effect for ipsilateral distractors. The strabismic group however had a larger difference between contralateral and ipsilateral distractors (Appendices 10.11 & 10.12). This generally supports hypothesis 1b that the effect in both groups of subjects can be considered equivalent.

Due to the lack of perception of images within the suppression area in strabismus hypothesis 1c proposed that saccade latency would be unaffected by distractors presented within the suppression area of the strabismic eye. Figure 6.1 showed that the effect in the strabismic eye was considerably less than that found in the fixing eye and both eyes. Statistical analysis of the saccade latency with and without distractors at

fixation (Appendix 10.4) showed that there was no significant difference supporting this hypothesis. However there was a significant difference in saccade latency for contralateral and ipsilateral distractors with contralateral distractors leading to longer latencies. This indicates that although the distractor effect is not evident at the original fixation point distractors within the suppression area do affect saccade latency. Hypothesis 1c is therefore rejected.

When individual subject data was examined the maximum effect produced from the strabismic eye appeared to occur when distractors were presented in the area of the anatomical fovea.

6.4.3 Saccade gain

Hypothesis 2a postulated that distractors presented binocularly and monocularly to the fixing eye would affect saccade gain, and this was supported as shown in Figure 6.4 and statistically (Appendices 10.17 and 10.18). The experiment revealed significant changes in saccade gain for ipsilateral distractors to the target. The effects in the fixing eye and both eyes were compared with the response in subjects with normal BSV from the dominant eye and both eyes. Figures 5.6 and 6.4 and statistical analysis (Appendices 10.21 and 10.24) showed that the effects with distractors in both eyes were equivalent however, the effect from the dominant eye was larger in the strabismic group. Hypothesis 2b was therefore supported for binocular distractors but rejected for distractors to the dominant (fixing) eye. This indicates that in strabismus, information from the fixing eye has a much greater effect on saccade accuracy than the dominant eye in normal BSV.

The effect of distractors presented to both eyes on gain was not found to be significantly different between the two groups (Appendices 10.23 and 10.24). However, the enhanced effect of binocular distractors, demonstrated in subjects with normal BSV in Experiment 4, was not present in the strabismic subjects possibly as the dominant eye had an increased effect. Statistical analysis of the strabismic group (Appendices 10.17 and 10.18) showed that there was no significant difference in the effect of distractors to both eyes and to the fixing eye. Hypothesis 2d was therefore supported.

Distractors in the strabismic eye had a variable effect on gain between subjects. The mean group data show that the effect is significantly different from the response with distractors presented to the fixing eye and both eyes (Figure 6.4 and Appendices 10.15

and 10.16). When considering differences between ipsilateral and contralateral distractors in the strabismic eye, gain was significantly affected depending on the side of the distractor and showed increased gain for ipsilateral distractors for 4° targets. Distractors presented within the suppression area of the strabismic eye therefore affected gain. Hypothesis 2c is therefore rejected.

6.4.4 Mechanism for the distractor effect in suppression

In strabismic subjects with suppression the maximum effect on latency, with distractors to the fixing eye and both eyes, was equivalent or greater in magnitude to that found in the observers with normal BSV. Whilst the maximum effect produced from the strabismic eye (distractors presented in the area of the anatomical fovea) was approximately one third of the size. The effects on saccade accuracy from distractors to the strabismic eye in subjects with suppression were small with two subjects having no response at all.

The reciprocal effects of distractor eccentricity on accuracy and latency have been taken to support the suggestion that two independent processes occur, one controlling the initiation of saccades (the WHEN system) and the other involved in computation of the spatial parameters (WHERE system), (Findlay, 1983; Becker & Jürgens, 1979). However more recently Olivier, Dorris and Munoz (1999) following recording of neuronal activity in the monkey suggest that both effects may be explained by a single mechanism. The superior colliculus has two distinct layers; the superficial layer is involved in visual functions and has a dominant input from retina and striate cortex. The deep layer is involved in translation of sensory signals into motor commands and receives input from cortical regions (LIP, FEF, SEF, SN). Intermediate layers are thought to form a motor map that codes amplitude and direction of saccades. Differing effects on these regions could affect saccade timing and not metrics.

Recordings in cortical neurons of cats with alternating esotropia and exotropia show only minimal excitatory input from the suppressed eye suggesting that the seat of suppression is within the visual cortex (Sengspiel, Blakemore, Kind & Harrad, 1994). The presence of a distractor effect from the strabismic eye during suppression may suggest that sub-cortical mechanisms exist despite the cortical loss of perception.

There are many studies that provide evidence for visual processing, in the absence of the geniculostriate pathway, mediated by sub-cortical pathways (Pöppel, Held & Frost,

1973; Weiskrantz, Warrington, Sanders & Marshall, 1974; Weiskrantz, 1987; Sanders, Warrington, Marshall & Weiskrantz, 1974; Zihl, 1980; Barbur, Forsyth & Findlay, 1988; Braddick, Atkinson, Hood, Harkness, Jackson & Vargha-Khadem, 1992). Of particular interest is the study by Rafel, Smith, Krantz, Cohen and Brennan (1990), which examined the latency of saccades made by hemianopic patients to stimuli presented in their intact visual field under conditions in which visual distractors appeared in their blind field. The findings were that saccade latency increased when distractors were presented in the blind field. A similar increase in latency could not be demonstrated in normal observers. These findings were taken as showing that the distractor effect was specific to the oculomotor system and may be observed only when the cortical visual pathway is inoperative, suggesting that the sub-cortical visual pathway is responsible for the distractor effect. Walker, Mannan, Maurer, Pambakian and Kennard (2000) however, revealed no evidence of blindsight inhibitory effects in hemianopic observers with cortical lesions. They conclude that the distractor effect is a normal characteristic of the saccadic system and may be related to the process of response competition involved in saccade target selection and suggest that this may be mediated by the deep colliculus, which depends on the corticotectal pathway for visual input.

If the distractor effect from the strabismic eye, as demonstrated in this current study, occurs via a sub-cortical retino-collicular route, then how can the variable effects be explained? Variability in the response was found; with different effects occurring for 4° and 8° targets and saccade latency was affected whilst only minimal changes to saccade accuracy were demonstrated. Holtzman (1984) reported that collicular 'vision' is of limited spatial resolution, which may offer one explanation for this. Physiology of the superior colliculus of monkeys has shown that receptive fields of collicular neurons are much larger than those of the visual cortex (Goldberg and Robinson, 1978). Hence localisation of the distractor would be limited thus having less effect on saccade accuracy.

It may be that there are explanations, other than sub-cortical processing, for the finding in this present study of a distractor effect in patients with suppression. It may be that a high sensitivity exists in suppression for detection of transient onset and offset of a target. This has been described in patients with destruction of the striate cortex who could detect and localise fast moving targets and flashed targets in his otherwise blind hemifield (Barbur, Forsyth & Findlay, 1988). This may mean that the briefly presented distractor was perceived cortically but failed to register consciousness to the subject.

As outlined in Chapter 1, normal rivalrous suppression, (occurring in subjects with normal BSV when presented with dissimilar stimuli to each eye), can be prevented if the stimuli are presented briefly (≤150ms). In such circumstances the stimuli appear as if superimposed (Kaufman 1963, O'Shea & Crassini 1984). Wolfe (1986) similarly demonstrated that, in six subjects with constant strabismus and suppression, suppression does not occur in a dark room when stimuli are briefly flashed for ≤150ms, suggesting that pathological suppression requires 150ms of stimulation to be made manifest. It is possible that under the different lighting levels and target/ distractor luminance that the 200ms distractor presentation prevented suppression. The method of dissociation used may also be a factor. The LCP shutters, operating at 80Hz out of phase to each eye, led to 12.5ms samples to each eye. This form of dissociation by time delay may have broken down the suppression.

Switching fixation during target and distractor presentations is another possibility but this was not evident from eye movement recordings in the experiments reported here. It may be that when the anatomical fovea of the strabismic eye is stimulated with a target different to that seen by the fixing eye then attention is swapped momentarily to the strabismic eye, breaking down the suppression.

The next experiment was designed to test the subjects' perception of the stimuli used for the distractor experiments.

6.5 Experiment 6: To determine visibility of the distractor

It is possible that the method of presenting distractors to the strabismic eye broke down suppression and hence gave a misleading result. To determine whether subjects with suppression perceived the distractor presented to the strabismic eye for 200ms during the saccade task the following experiment was carried out after Experiment 5. It was considered appropriate to perform this current experiment following the distractor experiment as subjects may have developed a strategy for detecting the distractor within the suppression area of the deviating eye or may have become more sensitive to presence of the distractor during the long distractor experiment.

6.5.1 Method

6.5.1.1 Participants

Five of the six strabismic subjects with suppression described in Experiment 5 of this chapter (subjects 2, 3, 4, 5 and 6) and two subjects with normal BSV from Experiment 4, Chapter 5 (subjects 1 and 3) were included in the study.

6.5.1.2 Design of the experiment

The experiment design was a detection task. The independent variables were; target position (4° and 8°), distractor position (0, ±2°, ±4°, ±6°, ±8°, ±10° and no distractor) and distractor condition (dominant eye, non-dominant eye and both eyes). The dependent variable was visibility of the distractor as indicated by a joystick response.

6.5.1.3 Procedure

The subjects were seated in a comfortable office chair 114cm from the translucent screen with the LCP shutters clamped in position. Before each block of trials the subjects were informed that all targets would initially appear in the centre of the screen and always move to the right and then back to the centre. This direction was maintained for all subsequent trials.

The 1° target cross (see Figure 5.2) was presented centrally to both eyes for a random period (500 to 1200ms) it then disappeared and immediately reappeared at either 4° or 8° on the horizontal axis for 500ms (nominally zero gap). The target then returned to the centre point before the next trial. In most trials a distractor appeared simultaneously with the onset of the 4° or 8° targets for 200ms. The eccentricity of the distractor varied along the horizontal axis randomly between -10, -8, -6, -4, -2, 0, +2, +4, +6, +8, +10° and no distractor as in Experiments 4 and 5 (see Figure 5.4).

Twenty saccade and distractor trials were presented in a 50 second test run. Six runs were completed to allow ten distractor presentations at each position (including no distractor). The experiment was performed three times; with distractors presented to the dominant eye, non-dominant eye and both eyes. The order of distractor presentation was randomised between subjects.

The subjects were instructed to look directly at the centre of the small target cross, positioned in the middle of the screen and, when it jumped to the right and back to the centre, to move their eyes as quickly and accurately as possible to continue looking at the centre of the cross. They were told that sometimes as the target jumped to the right a circle (the distractor) would appear anywhere on the screen. They were instructed to indicate using a joystick every time the distractor was seen.

6.5.2 Results

The joystick responses were recorded and analysed off line following the experiment. The number of correct responses (or hits) for each distractor position and the number of 'visible' responses with no distractor (false positives) was determined.

The number of correct responses, for each subject, of 10 trials in each distractor position is shown in Figure 6.7. The horizontal black line represents the number of false positive responses in the no distractor condition.

From Figure 6.7 it is clear that the binocular subjects reliably saw the distractor under all 3 conditions whilst the results demonstrate that the distractor was only visible when presented to the dominant (fixing) eye or both eyes in the strabismic subjects with suppression.

Signal detection theory was used to measure accuracy of these responses (Green & Swets, 1966). Signal detection theory combines the hits and false positives to calculate an index of accuracy, d'. For details of d' calculations see Appendix 10.27. These results show high d' values for all distractor positions for all 3 distractor conditions in both of the binocular subjects. This is in contrast to all of the five strabismic subjects with suppression who had high d' values for all distractor positions in the dominant eye and both eyes conditions but had extremely low d' values for all distractor positions when presented to the non-dominant (strabismic) eye.

6.5.3 Conclusion

The results suggest that the distractor was highly visible and easily detected by binocular subjects under all conditions and by strabismic subjects when presented to both eyes or to the fixing eye. However, when the distractor was presented to the strabismic eye the subjects with suppression did not perceive it.

The response to distractors presented in the strabismic eye reported earlier in this chapter was therefore not due to the method of distractor presentation breaking down suppression. Distractors within the suppression area that were not perceived affected saccade latency and gain. It would appear therefore that targets presented within the suppression area affect saccade programming.

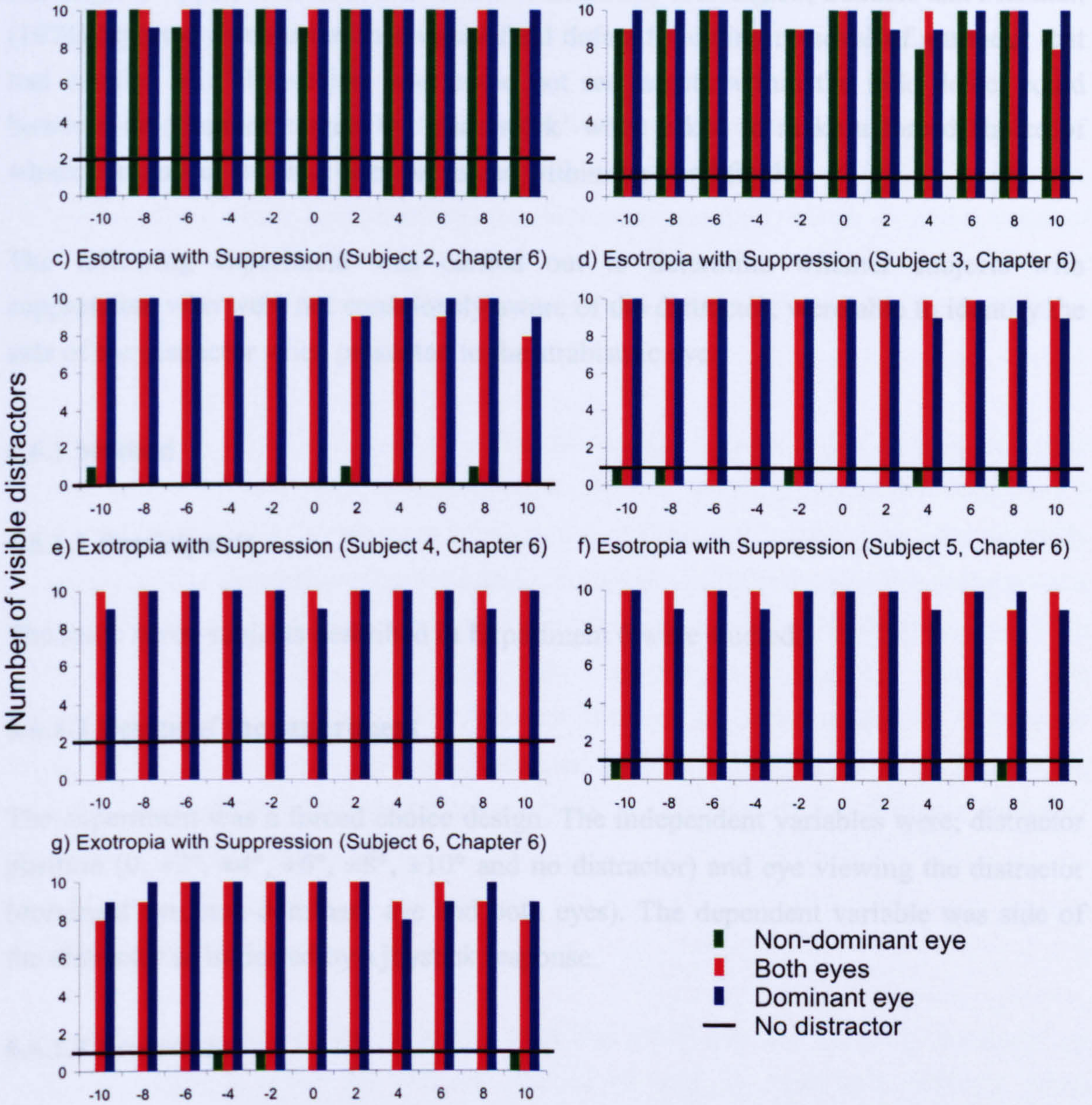


Figure 6.7: The number of visible distractors at each eccentricity for 2 subjects with normal BSV (a & b), and 5 strabismic subjects with suppression (c to g). Responses were recorded from each subject using a joystick to indicate when they were aware of a distractor at any location. The subjects were making saccadic eye movements to a target moving from the centre to 4 and 8° right of centre during the detection task as described for the distractor experiments in chapters 5 and 6. The black horizontal line represents the number of no distractor presentations in which a visible response was made (i.e. false positives).

6.6 Experiment 7: To determine awareness of the distractor

It is possible that although subjects reported lack of perception of the distractor that they may have been sub-consciously aware of the distractor. Such responses have been reported in subjects with visual cortex damage who were unable to see targets in the blind field but were able to make accurate eye movements to fixate them, so called blindsight (Pöppel, Held & Frost, 1973). Weiskrantz, Warrington, Sanders and Marshall (1974) reported a subject with a visual field defect following removal of a tumour that had invaded V1. The subject who could not see targets within the field defect could however discriminate targets by 'guesswork' when asked to make a forced choice of which stimulus of two had been presented within the blind field.

The following experiment was carried out to determine whether subjects with suppression, who were not consciously aware of the distractor, were able to identify the side of the distractor when presented to the strabismic eye.

6.6.1 Method

6.6.1.1 Participants

The same seven subjects described in Experiment 6 were studied.

6.6.1.2 Design of the experiment

The experiment was a forced choice design. The independent variables were; distractor position (0, ±2°, ±4°, ±6°, ±8°, ±10° and no distractor) and eye viewing the distractor (dominant eye, non-dominant eye and both eyes). The dependent variable was side of the distractor as indicated by a joystick response.

6.6.1.3 Procedure

The experimental set-up, target and distractor stimuli were identical to that described in Experiment 6. The only difference in procedure was the instructions given to the subjects. They were instructed to look directly at the centre of the small target cross positioned in the middle of the screen and to move their eyes as quickly and accurately as possible to maintain fixation of it when it jumped to the right and back to the centre. They were told that sometimes as the target jumped to the right, a circle (the distractor)

would appear anywhere on the screen. They were instructed to indicate using a joystick whether the circle appeared to the right or left of the central original fixation point. If they were unsure of the direction they were told to guess.

6.6.2 Results

The joystick responses were recorded and analysed off line following the experiment. The number of left responses for each distractor condition was determined.

Figure 6.8 shows the number of left responses out of 10 trials, for each subject, in each distractor position. If the side of distractor was correctly indicated with the joystick then the graph would show a value of ten for distractor positions -10 to -2, and a value of zero for positions +2 to +10. The response of forced choice guessing when no distractor was presented represents the subject's bias in response when nothing was visible to them.

From Figure 6.8 a and b it is clear, generally, that the two binocular subjects correctly indicated the direction of the distractor under all three viewing conditions. Figure 6.8 c to g shows that in the strabismic subjects the distractor direction was only correctly indicated when presented to the dominant (fixing) eye or to both eyes, the response was clearly different with distractors presented to the non-dominant (strabismic) eye. With distractors presented in all positions to the non-dominant (strabismic) eye all five subjects responded similarly to their response in the no distractor condition. They either randomly guessed the side giving approximately 50% of responses in each direction (subjects 4 and 5) or showed a bias by maintaining a single direction for the majority of presentations (subjects 2, 3 & 6).

6.6.3 Conclusion

The results suggest that the distractor was highly visible and correctly localised by binocular subjects under all viewing conditions and by strabismic subjects when presented to both eyes or to the fixing eye. However, in strabismic subjects when the distractor was presented to the strabismic eye it was not perceived and they did not have any sub-conscious awareness of it.

The response to distractors presented in the strabismic eye reported earlier in this chapter, occurred despite lack of awareness of the distractor. Distractors within the suppression area that were not perceived affected saccade latency and gain.

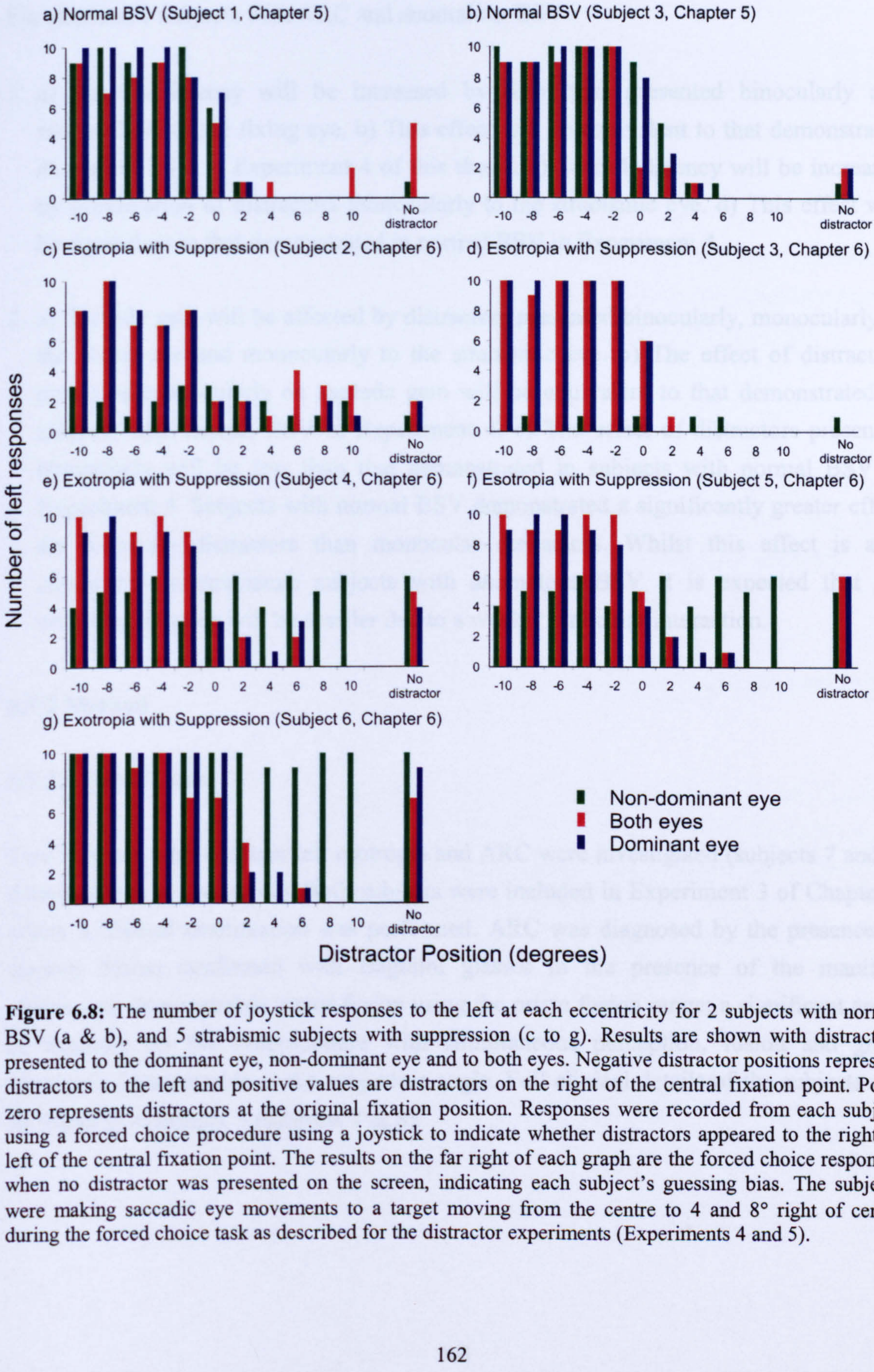


Figure 6.8: The number of joystick responses to the left at each eccentricity for 2 subjects with normal BSV (a & b), and 5 strabismic subjects with suppression (c to g). Results are shown with distractors presented to the dominant eye, non-dominant eye and to both eyes. Negative distractor positions represent distractors to the left and positive values are distractors on the right of the central fixation point. Point zero represents distractors at the original fixation position. Responses were recorded from each subject using a forced choice procedure using a joystick to indicate whether distractors appeared to the right or left of the central fixation point. The results on the far right of each graph are the forced choice responses when no distractor was presented on the screen, indicating each subject's guessing bias. The subjects were making saccadic eye movements to a target moving from the centre to 4 and 8° right of centre during the forced choice task as described for the distractor experiments (Experiments 4 and 5).

6.7 Experiment 8: The distractor effect in strabismus with ARC

6.7.1 Hypotheses

For strabismic subjects with ARC and anomalous BSV:

1. a) Saccade latency will be increased by distractors presented binocularly and monocularly to the fixing eye. b) This effect will be equivalent to that demonstrated in normal BSV in Experiment 4 of this thesis. c) Saccade latency will be increased by presentation of distractors monocularly to the strabismic eye. d) This effect will be equivalent to that demonstrated in normal BSV in Experiment 4.

2. a) Saccade gain will be affected by distractors presented binocularly, monocularly to the fixing eye and monocularly to the strabismic eye. b) The effect of distractors presented monocularly on saccade gain will be equivalent to that demonstrated in subjects with normal BSV in Experiment 4. c) The effect of distractors presented binocularly will be less than that demonstrated in subjects with normal BSV in Experiment 4. Subjects with normal BSV demonstrated a significantly greater effect for binocular distractors than monocular distractors. Whilst this effect is also anticipated in strabismic subjects with anomalous BSV it is expected that the binocular increase will be smaller due to a weaker binocular interaction.

6.7.2 Method

6.7.2.1 Participants

Two subjects with constant left esotropia and ARC were investigated (subjects 7 and 8, details shown in Table 6.9). Both subjects were included in Experiment 3 of Chapter 4 where a clinical examination was performed. ARC was diagnosed by the presence of sensory fusion confirmed with Bagolini glasses in the presence of the manifest strabismus; demonstrable motor fusion using the prism fusion range; a significant angle of anomaly on the synoptophore with simultaneous perception, fusion and gross stereopsis demonstrable at the subjective angle. Full clinical details of the subjects can be found in Appendix 5 (subjects 7 & 8).

Subj	Age (years)	VA		Strabismus	PCT 1.14m (Δ)	Retinal corresp.	Suppression	Abnormal BSV		
		RE	LE					Sensory	motor	SV
7	20.9	-0.1	0.0	LET	12 BO	ARC	no	yes	yes	gross
8	18.1	-0.1	0.0	LET	10 BO	ARC	no	yes	yes	200''

Table 6.9: Summary of clinical details of two subjects with strabismus and ARC. VA = log MAR visual acuity, PCT = prism cover test, LET = left esotropia, Δ = prism dioptre, BO = prism base out, SV = stereoscopic vision.

6.7.3 Results

A preliminary trial showed that, whilst fixating the central fixation target presented to both eyes, both observers were aware of the presence of the distractor when presented to the fixing eye, both eyes and unlike the strabismic group, to the strabismic eye.

The mean saccade latency and gain for the no distractor condition for each subject is shown in Table 6.10. It can be seen that these two subjects had different behaviour, subject 7 having latencies reflecting the mean of the subjects 1-6, whilst subject 8 had short latency saccades. Subject 7 consequently had gains closer to 1.0 with lower standard deviations than subject 8 who had relatively low saccade accuracy. The subjects were therefore considered individually.

Tables 6.11 and 6.12 show individual subject data for saccade latency and gain in each distractor location for the three distractor conditions.

Figure 6.9 shows the mean saccade latency plotted as a function of distractor eccentricity with distractors to both eyes, fixing eye and strabismic eye for each subject. A slightly atypical distractor effect on latency, similar for presentations to the fixing eye, strabismic eye and both eyes is seen for both subjects.

a)

Mean saccade latency with no distractor		
Subject	**4°**	**8°**
7	166.05 SD 24.07	161.46 SD 14.59
8	134.30 SD 18.20	132.80 SD 16.41

b)

Mean saccade gain with no distractor		
Subject	**4°**	**8°**
7	1.012 SD 0.170	0.972 SD 0.118
8	1.041 SD 0.244	0.853 SD 0.220

Table 6.10: Mean saccade latency (a) and gain (b) with no distractor for individual subjects with strabismus and ARC. SD = standard deviation.

a)

Distractor fixing eye											
Subject	-10	-8	-6	-4	-2	0	2	4	6	8	10
7	166 00	160 00	165.71	166 88	170.59	195.00	177.78	164.29	162.50	160.00	172.86
8	147 50	159 58	139 58	144 41	151.00	165.42	141.25	134 09	142.31	124 09	140.83
Mean	156.75	159.79	152.65	155.64	160.79	180.21	159.51	149.19	152.40	142.05	156.85
SD	13.08	0.29	18.48	15.88	13.85	20.92	25.83	21.35	14.28	25.39	22.64
SE	9.25	0.21	13.07	11.23	9.79	14.79	18.26	15.10	10.10	17.95	16.01

Distractor strabismic eye											
Subject	-10	-8	-6	-4	-2	0	2	4	6	8	10
7	159.33	161.56	162.31	170.25	168.00	187.33	172 06	161.56	159 71	174.17	178.33
8	142 86	130.94	151 56	140.91	147.50	146.15	135.94	143.33	131.11	135.00	134.38
Mean	151.10	146.25	156.94	155.58	157.75	166.74	154.00	152.45	145.41	154.58	156.35
SD	11.65	21.66	7.60	20.75	14.50	29.12	25.54	12.89	20.22	27.70	31.08
SE	8.24	15.31	5.37	14.67	10.25	20.59	18.06	9.11	14.30	19.58	21.98

Distractor both eyes											
Subject	-10	-8	-6	-4	-2	0	2	4	6	8	10
7	165 75	164 12	162 94	171 88	173 44	197.86	181.14	161.15	161.43	163.85	170.50
8	149 64	146.94	150.00	150.71	152.19	168.33	146 92	131.67	140.91	128.44	127.00
Mean	157.70	155.53	156.47	161.29	162.81	183.10	164.03	146.41	151.17	146.14	148.75
SD	11.39	12.14	9.15	14.96	15.03	20.88	24.19	20.85	14.51	25.04	30.76
SE	8.05	8.59	6.47	10.58	10.63	14.76	17.11	14.74	10.26	17.70	21.75

b)

Distractor fixing eye											
Subject	-10	-8	-6	-4	-2	0	2	4	6	8	10
7	167.11	161.11	169 44	165.26	179 69	203 89	176.56	184.47	162.65	161 84	160.63
8	138.13	133 50	144 00	137.50	146.82	159.12	151.50	150.36	142.00	127.37	127.50
Mean	152.62	147.31	156.72	151.38	163.25	181.50	164.03	167.42	152.32	144.61	144.06
SD	20.49	19.52	17.99	19.63	23.24	31.66	17.72	24.12	14.60	24.38	23.42
SE	14.49	13.81	12.72	13.88	16.43	22.39	12.53	17.06	10.32	17.24	16.56

Distractor strabismic eye											
Subject	-10	-8	-6	-4	-2	0	2	4	6	8	10
7	167.65	158 61	165 23	162 50	173.33	184.00	192.78	179.74	162.50	160.00	163.44
8	138.16	131.07	138 53	133 89	139.41	141.33	130 94	133.85	136.43	132.50	126.15
Mean	152.90	144.84	151.88	148.19	156.37	162.67	161.86	156.79	149.46	146.25	144.80
SD	20.85	19.47	18.88	20.23	23.99	30.17	43.73	32.45	18.44	19.45	26.36
SE	14.74	13.77	13.35	14.31	16.96	21.33	30.92	22.95	13.04	13.75	18.64

Distractor both eyes											
Subject	-10	-8	-6	-4	-2	0	2	4	6	8	10
7	167.00	175.00	172.00	174.21	186.39	200 00	213.33	166.11	157.62	147.73	166.00
8	136.32	133 93	142 06	144.17	147.06	151.00	136.56	135.77	130.00	128.13	136.92
Mean	151.66	154.46	157.03	159.19	166.72	175.50	174.95	150.94	143.81	137.93	151.46
SD	21.70	29.04	21.17	21.24	27.81	34.65	54.29	21.45	19.53	13.86	20.56
SE	15.34	20.54	14.97	15.02	19.67	24.50	38.39	15.17	13.81	9.80	14.54

Table 6.11: The effect of distractors on saccade latency (ms) for each distractor position for two subjects with manifest strabismus and ARC, a) 4° targets, b) 8° targets. SD = standard deviation, SE = standard error

a)

Distractor fixing eye											
Subject	-10	-8	-6	-4	-2	0	2	4	6	8	10
7	1 064	1 036	1 026	1.030	1 001	0.975	0.891	1.039	1.249	1.369	1 239
8	0.945	0.988	1.044	1.031	1 014	1.065	1.019	0.901	1.311	1.523	1.727
Mean	1.005	1.012	1.035	1.030	1.007	1.020	0.955	0.970	1.28	1.45	1.48
sd	0.084	0.034	0.013	0.001	0.009	0.064	0.090	0.098	0.04	0.11	0.35
se	0.060	0.024	0.009	0.001	0.007	0.045	0.064	0.069	0.03	0.08	0.24

Distractor fixing eye											
Subject	-10	-8	-6	-4	-2	0	2	4	6	8	10
7	1 094	1 021	1 019	1.082	1.095	1 042	0.965	1.055	1.317	1.228	1.193
8	1 023	0 955	0.998	0 930	0 941	1.016	1.008	1.088	1.395	1.478	1.692
Mean	1.058	0.988	1.008	1.006	1.018	1.029	0.987	1.072	1.356	1.353	1.442
sd	0.050	0.046	0.015	0.108	0.109	0.018	0.030	0.023	0.055	0.177	0.353
se	0.036	0.033	0.011	0.076	0.077	0.013	0.021	0.017	0.039	0.125	0.250

Distractor fixing eye											
Subject	-10	-8	-6	-4	-2	0	2	4	6	8	10
7	1 064	0 968	0.992	0 985	0 972	1 010	0.912	1 030	1.301	1.357	1 499
8	1.051	0.930	0.941	1.026	0.914	1.117	1.016	1.151	1.278	1.790	2.200
Mean	1.058	0.949	0.966	1.005	0.943	1.064	0.964	1.091	1.289	1.573	1.850
sd	0.009	0.027	0.036	0.029	0.040	0.076	0.074	0.085	0.016	0.306	0.496
se	0.006	0.019	0.025	0.021	0.029	0.053	0.052	0.060	0.012	0.217	0.351

b)

Distractor fixing eye											
Subject	-10	-8	-6	-4	-2	0	2	4	6	8	10
7	0 982	0.983	0 931	0.994	0.991	1.020	0.729	0.722	0.808	0.958	1.049
8	0 880	0.791	0 890	0 846	0.890	0.847	0 723	0.726	0.723	0.855	0.855
Mean	0.931	0.887	0.910	0.920	0.940	0.933	0.726	0.724	0.765	0.906	0.952
SD	0.072	0.136	0.029	0.104	0.071	0.122	0.004	0.003	0.060	0.072	0.137
SE	0.051	0.096	0.021	0.074	0.050	0.086	0.003	0.002	0.042	0.051	0.097

Distractor strabismic eye											
Subject	-10	-8	-6	-4	-2	0	2	4	6	8	10
7	0 989	0 962	0 974	0 992	0.985	1.003	0.879	0.743	0.847	0.950	1.024
8	0 810	0.866	0.801	0.751	0.795	0.802	0.782	0.679	0.681	0.767	0.757
Mean	0.900	0.914	0.888	0.871	0.890	0.902	0.830	0.711	0.764	0.859	0.890
SD	0.126	0.068	0.123	0.170	0.134	0.142	0.069	0.045	0.117	0.129	0.188
SE	0.089	0.048	0.087	0.120	0.095	0.101	0.049	0.032	0.083	0.091	0.133

Distractor both eyes											
Subject	-10	-8	-6	-4	-2	0	2	4	6	8	10
7	1.003	0 999	0.946	0 996	0.953	0.984	0.753	0.644	0.757	0.946	1.037
8	0.866	0.925	0 831	0.799	0.852	0.902	0.836	0.738	0.776	0.846	0.919
Mean	0.934	0.962	0.889	0.898	0.903	0.943	0.794	0.691	0.766	0.896	0.978
SD	0.097	0.052	0.082	0.139	0.071	0.058	0.059	0.067	0.014	0.071	0.083
SE	0.069	0.037	0.058	0.098	0.051	0.041	0.042	0.047	0.010	0.050	0.059

Table 6.12: The effect of distractors on saccade gain for each distractor position for two subjects with manifest strabismus and ARC, a) 4° targets, b) 8° targets. SD = standard deviation, SE = standard error.

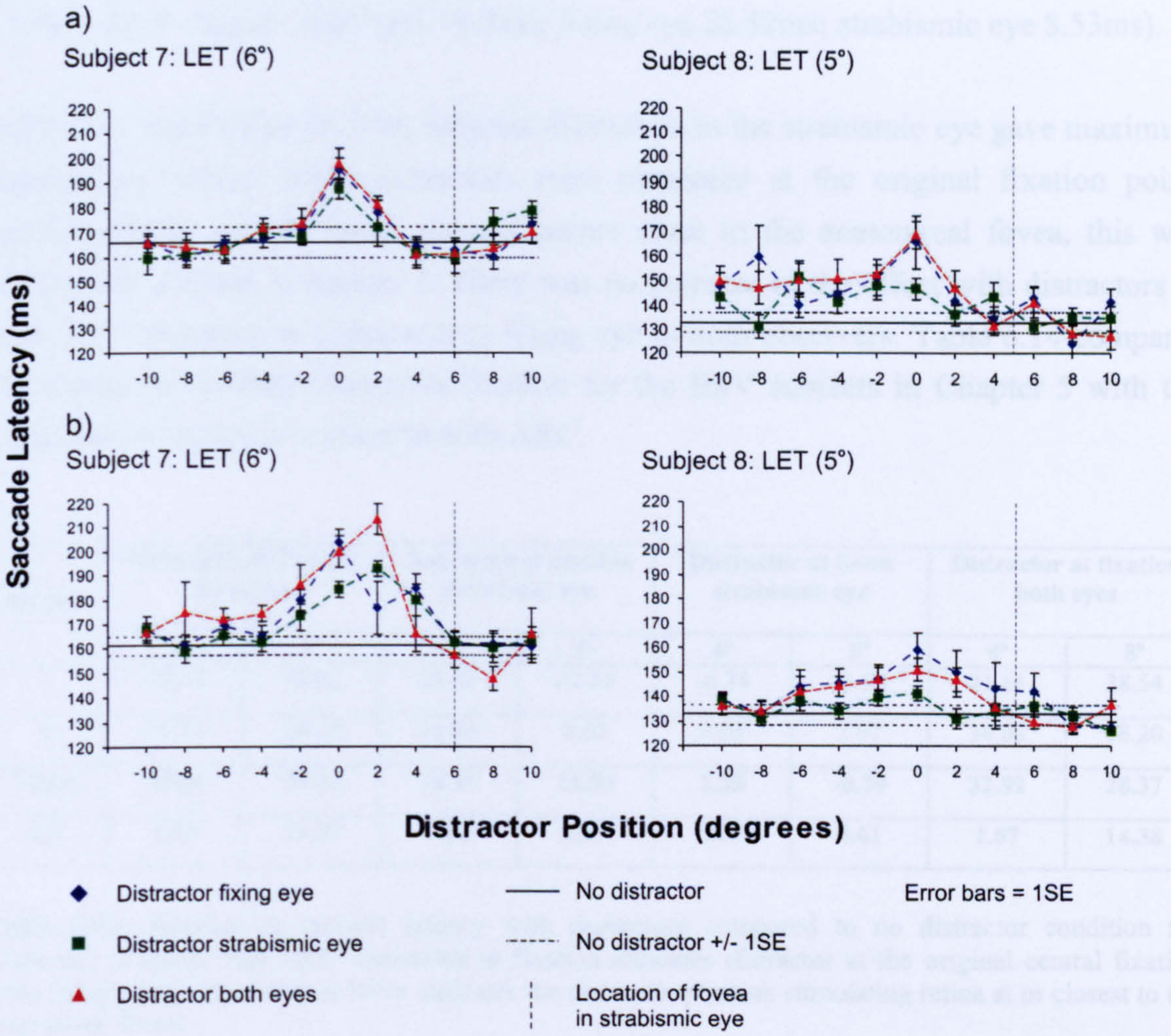


Figure 6.9: The effect of distractors presented to the fixing eye, strabismic eye and both eyes on saccade latency for two strabismic observers with ARC. a) 4° targets, b) 8° targets. LET = left esotropia, SE = standard error.

For 4° targets in all distractor conditions subject 7 had no increase in latency for contralateral distractors although did have an increase with distractors at fixation (for 4° targets: both eyes 31.8ms; fixing eye 29.0ms; strabismic eye 21.3ms and for 8° targets: both eyes 38.5ms; fixing eye 42.4ms; strabismic eye 22.5ms). An increase for contralateral distractors was present for 8° targets but atypically, for both eyes and strabismic eye distractors the maximum increase occurred at +2°. For fixing eye presentation the peak increase was at the original fixation point but longer latencies were also evident for ipsilateral distractors.

Subject 8 demonstrated increased latency for all distractor conditions with maximum increase at the original fixation point. The effect was weaker for strabismic eye

presentations (for 4° targets: both eyes 34.0ms; fixing eye 31.1ms; strabismic eye 11.9ms; for 8° targets: both eyes 18.2ms; fixing eye 26.32ms; strabismic eye 8.53ms).

Table 6.13 shows that for both subjects distractors in the strabismic eye gave maximum increase in latency when distractors were presented at the original fixation point, stimulating the pseudo-fovea and not points close to the anatomical fovea, this was particularly evident in subject 7. There was no increase in the effect with distractors to both eyes compared to distractors to fixing eye in both observers. Table 6.14 compares the change in saccade latency at fixation for the BSV subjects in Chapter 5 with the mean data from the two subjects with ARC.

Subject	Distractor at fixation fixing eye		Distractor at fixation strabismic eye		Distractor at fovea strabismic eye		Distractor at fixation both eyes	
	4°	8°	4°	8°	4°	8°	4°	8°
7	28.95	42.43	21.28	22.54	-6.34	-3.55	31.81	38.54
8	31.12	26.32	11.85	8.53	9.03	2.97	34.03	18.20
Mean	**30.04**	**34.38**	**16.57**	**15.54**	**1.35**	**-0.29**	**32.92**	**28.37**
SD	**1.53**	**11.39**	**6.67**	**9.91**	**10.87**	**4.61**	**1.57**	**14.38**

Table 6.13: Increase in saccade latency with distractors compared to no distractor condition for strabismic subjects with ARC. Distractor at fixation indicates distractor at the original central fixation point (point zero), distractor at fovea indicates the distractor position stimulating retina at or closest to the anatomical fovea.

Distractor	4° targets		8° targets	
	BSV	ARC	BSV	ARC
Dominant eye	53.0	30.0	47.5	34.4
Non-dominant eye	41.5	16.6	44.2	15.5
Both	65.9	32.9	59.2	28.4

Table 6.14: Increase in saccade latency (ms) for each distractor condition, with distractors at the original fixation point, for five subjects with BSV and two subjects with ARC.

Figure 6.10 shows the mean saccade gain plotted as a function of distractor eccentricity with distractors presented to both eyes, dominant eye and non-dominant eye for each subject. The distractor effect on gain was similar for both eyes, fixing eye and strabismic eye presentations for both subjects. For both subjects the response was typical of the normal response, subject 8 had a reduced effect for 8° saccades but this subject did generally have variable saccade gain as shown in Table 6.10b. An increased effect with distractors to both eyes compared to fixing eye presentation is evident for 4°

targets similar to that shown in the binocular subjects reported in Experiment 4, see Table 6.15).

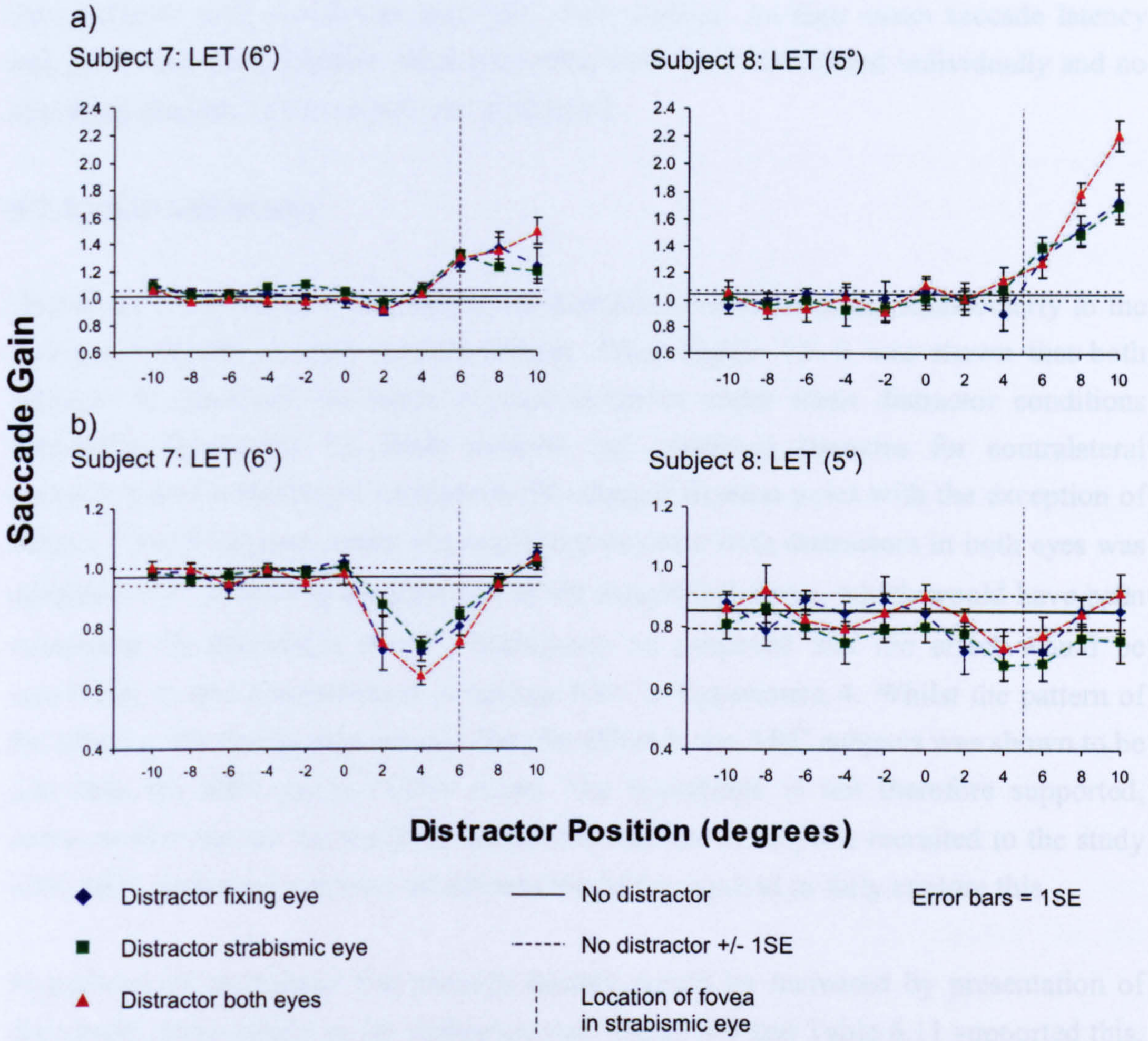


Figure 6.10: The effect of distractors presented to the fixing eye, strabismic eye and both eyes on saccade gain for two strabismic observers with ARC. a) 4° targets, b) 8° targets. LET = left esotropia, SE = standard error.

Subject/ group	Dominant eye		Non-dominant		Both		Enhanced binocular effect	
	4°	8°	4°	8°	4°	8°	4°	8°
7	0.227	0.243	0.181	0.093	0.487	0.219	**0.260**	**-0.024**
8	0.686	0.130	0.651	0.071	1.159	0.017	**0.473**	**-0.113**
BSV	0.240	0.232	0.352	0.135	0.824	0.382	**0.472**	**0.150**

Table 6.15: Summary of maximum change in saccade gain with distractors for two subjects with strabismus and ARC and the mean of five subjects with BSV (from Experiment 4). Change in gain for 4° targets is taken from distractors at +10° and for 8° targets from +2°. The enhanced binocular effect is the change in gain for distractors to both eyes minus change in gain for distractors presented monocularly. Monocular values are taken from the eye with maximum change in gain.

6.7.4 Discussion

Two subjects with strabismus and ARC were studied. As their mean saccade latency and gain were quite different from each other they were considered individually and no statistical analysis of the results was performed.

6.7.4.1 Saccade latency

Hypothesis 3a postulated that distractors presented binocularly and monocularly to the fixing eye would increase saccade latency. From Figure 6.9 it was shown that both subjects demonstrated increased saccade latencies under these distractor conditions supporting hypothesis 1a. Both subjects had increased latencies for contralateral distractors and a maximum increase at the original fixation point with the exception of subject 7 for 8° targets, where the maximum increase with distractors in both eyes was shifted to +2°. This is in the direction of the anatomical fovea, which would have been stimulated by distractors at +6°. Hypothesis 1b proposed that the effect would be equivalent to that demonstrated in normal BSV in Experiment 4. Whilst the pattern of the effect in the two groups was similar, the effect in the ARC subjects was shown to be less than the BSV group (Table 6.14). The hypothesis is not therefore supported, however this may be the result of the limited number of subjects recruited to the study with ARC. Increased numbers of subjects would be required to fully explore this.

Hypothesis 1c postulated that saccade latency would be increased by presentation of distractors monocularly to the strabismic eye, Figure 6.9 and Table 6.11 supported this. Hypothesis 1d proposed that the effect would be equivalent to that demonstrated in normal BSV. Whilst a similar pattern and location of the response was found the effect from the strabismic eye was much less than the non-dominant eye in the BSV group.

In subjects with strabismus and suppression the effect on latency with distractors presented to the strabismic eye was greatest when distractors were presented in a position stimulating the expected location of the anatomical fovea. This was not the case in the two observers with ARC where distractors presented at the original fixation point (i.e. to the pseudo-fovea) had a greater effect on latency than distractors presented to the anatomical fovea. The pseudo-fovea (+6° nasal to anatomical fovea for subject 7 and +5° nasal to anatomical fovea for subject 8) in the two observers studied had maximum inhibitory effect over saccades. It appears therefore that in ARC there is a

possible cortical and/or sub-cortical retinotopic re-mapping involved in programming of saccades.

6.7.4.2 Saccade gain

Hypothesis 2a proposed that saccade gain would be affected by distractors presented binocularly, monocularly to the fixing eye and monocularly to the strabismic eye. This was supported (as shown in Figure 6.10). The response in the two subjects with ARC showed quite different magnitudes. Subject 7 had an equivalent effect to the BSV group with dominant (fixing) eye distractors whilst the effect was less than the binocular subjects in the non-dominant eye. Subject 8 had a larger response from the dominant and non-dominant eyes than the BSV subjects for 4° targets but a reduced response for 8° targets. Hypothesis 2b postulated that the effect of distractors, presented monocularly, on saccade gain would be equivalent to that demonstrated in subjects with normal BSV in Experiment 4. Due to variability in the response of the two subjects this was not conclusively confirmed.

Hypothesis 2c was also somewhat inconclusive. It proposed that the effect of distractors presented binocularly would be less than that demonstrated in subjects in Experiment 4 with normal BSV. Subjects with normal BSV demonstrated a significantly greater effect for binocular distractors than monocular distractors. Whilst this effect was also anticipated in strabismic subjects with anomalous BSV it was expected that the binocular increase would be smaller due to a weaker binocular interaction. Table 6.14 showed the enhanced binocular effect for the two subjects with ARC compared to the mean effect in the BSV group. For 4° targets both ARC subjects have a large increase in the binocular effect and this is comparable to the BSV subjects in subject 8. For 8° targets however both ARC subjects have less change in gain for distractors presented binocularly than when presented to the dominant eye only.

It can be seen from Table 6.16 that the effect on the dominant eye of the strabismic subjects with suppression is much larger than in BSV subjects or those with ARC and anomalous binocular vision. This may indicate that the fixing eye primarily drives saccade generation in strabismus, with input to saccade generators from the fixing eye having more influence over saccade accuracy. This table also highlights the small, enhanced binocular response in strabismic subjects (which resulted from subjects 3 and 6), greater enhanced binocular response in anomalous BSV and largest enhanced binocular response in normal BSV. Saccade generation therefore appears to be affected

by sensory status. It is possible that true binocular interaction (summation) may only be claimed by the BSV group, as this is the only situation where the binocular response is greater than the sum of the monocular results.

Distractor	BSV	Strabismus & suppression	Strabismus ARC
Dominant eye	0.240	0.587	0.467
Non-dominant eye	0.352	0.187	0.426
Both eyes	0.824	0.770	0.834
Enhanced binocular effect	**0.472**	**0.183**	**0.367**

Table 6.16: Summary of maximum change in saccade gain with distractors for each subject group. Group mean data for 4° target amplitude shown for five subjects with BSV (reported in Experiment 4), six subjects with manifest strabismus and suppression (Experiment 5) and two subjects with manifest strabismus, ARC and anomalous binocular vision (Experiment 8). The enhanced binocular effect is the change in gain for distractors to both eyes minus change in gain for distractors presented monocularly. Monocular values are taken from the eye with maximum change in gain, i.e. dominant eye for strabismic groups and non-dominant eye in BSV group.

6.7.4.3 Mechanism for the distractor effect in ARC

The strabismic eye distractor effect on saccade latency in ARC was localised similarly to subjects with normal BSV, such that the maximum effect on latency was at the original fixation point stimulating nasal retina (pseudo-fovea). This may suggest that a collicular retinotopic shift in corresponding points equivalent to the angle of deviation occurs.

The effect with binocular distractors was slightly larger than monocular distractors in ARC but this did not reach the magnitude of increase seen for subjects with normal BSV. Presence of anomalous BSV gave rise to a small, enhanced effect.

Campos (1980) and Campos and Chiesi (1983) found larger binocular VEP than monocular VEP responses in strabismus with ARC, providing evidence for binocular vision in strabismus and perhaps supporting the idea of cortical retinotopic re-mapping. A neuroanatomic substrate for such re-mapping is suggested by the results of Berman and Payne (1983), who found that induced strabismus in kittens prevents the reduction in dendritic arborisation normally seen during maturation of the visual cortex. Theoretically this would make binocular interaction possible between cortical areas separated by a distance more than typically the case, such as a re-mapping in ARC. However there is no direct evidence that this actually occurs, topography of the VEP response has not confirmed a shift at any cortical site (areas 17 and 18) contributing to

the pattern-onset VEP (McCormack, 1975; McCormack, 1990). Topography of the VEP is the spatial distribution of VEP amplitude over the posterior scalp and is correlated to retinotopic mapping of the visual cortex (Jeffreys & Axford, 1972a & b). The technique used in the studies by Campos (1980) and Campos and Chiesi (1983) and McCormack (1990) was considerably different, as the stimuli used by Campos (1980) and Campos and Chiesi (1983) were large and not specifically directed at anomalously corresponding points, as was the case for the work of McCormack (1990). Hence the increased binocular response recorded in the former papers may be produced from different retinal regions in the two eyes, which activate physiologically separate cortical points whose electrical responses sum at the recording electrode.

Lack of evidence for re-mapping of cortical cells in ARC as discussed above may therefore suggest that the distractor effect seen in this current study may be explained by re-mapping in the superior colliculus. There is evidence for the existence of a purely sub-cortical route for eliciting goal directed saccades in the absence of cortical perception, in which the superior colliculus receives direct visual information to allow generation of saccades (Cowey & Stoerig, 1991). McCormack (1990) does acknowledge that it is possible that changes to the deviating eyes retinotopic mapping could occur at sites beyond the visual cortex or in the brain stem and suggests that the search for a physiological basis of ARC should be focussed on these other sites.

6.8 Final conclusion

In strabismus, with suppression and ARC, increased saccade latency occurred when distractors were presented to the strabismic eye compared to the no distractor condition. In all subjects with suppression the effect on latency, with distractors presented to the strabismic eye, was maximum when distractors were presented towards the location of the anatomical fovea. This was not the case in the two observers with ARC where distractors presented at the original fixation point (i.e. to the pseudo-fovea) had a greater effect on latency than distractors presented to the anatomical fovea.

The distractor effect on saccade accuracy was normal in the strabismic eye in ARC but only minimally affected in 4 of the 6 observers with suppression. An increased effect occurred with binocular distractor presentations compared to monocular presentation to the fixing eye (comparable to BSV subjects) in strabismic subjects with ARC but not in those with suppression.

Despite lack of awareness of, and inability to localise the distractor presented to the strabismic eye, saccade planning was affected by the presence of a distractor. Mechanisms to explain such results may include sub-cortical retino-collicular pathways or high sensitivity in suppression for detection of transient onset and offset of a target such that briefly presented targets are registered cortically but fail to reach conscious perception for the subject.

Experiment 5 demonstrated that peripheral distractors within the suppression area affect saccade generation. The experiments of Chapter 7 investigate this further by exploring saccade generation in response to the central fixation target within the suppression area.

Chapter 7

Saccade adaptation in normal BSV and strabismus

Chapter 6 revealed evidence of peripheral distractors presented within the suppression area affecting saccade programming. This chapter investigates the influence of the central fixation target in the strabismic eye, also presented within the suppression area, on saccade generation. Disconjugate saccade adaptation is studied in this instance in a group of subjects with constant strabismus and suppression with no clinical evidence of binocular vision or ARC. A group of subjects with normal BSV is also investigated to compare the responses.

7.1 Introduction

Horizontal saccades are naturally disconjugate, with abducting saccades being faster and slightly larger than adducting saccades (Kapoula, Hain, Zee & Robinson, 1987; Collewijn, Erkelens & Steinman, 1988; de Faber, van Rijn & Collewijn, 1994). This gives rise to relative divergence of the eyes. In normal BSV this is small where typically, for horizontal saccades of <20° from the primary position, the two eyes differ by <0.5° (Collewijn, Erkelens & Steinman, 1988). 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, on-going feedback is not possible, therefore a learning process is involved in saccade adaptation.

Changes to the visual system, such as natural aging, fatigue or disease processes, may lead to saccade adaptation to maintain comfortable BSV. Kommerell, Olivier and Theopold (1976) noted that patients with acquired unilateral nerve palsy could adjust the amplitude of their saccades depending on which eye was forced to view. Abel, Schmidt, Dell'Osso and Daroff (1978) observed the adaptive changes in saccades in a patient who had a sudden onset medial rectus paresis. They occluded the non-affected eye for one 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 Robinson (1980) confirmed the existence of adaptive capabilities of the saccadic system in monkeys who 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 (Deubel, Wolf & Hauske, 1986; Deubel, 1987) and electronic feedback systems (Albano & King, 1989). This work will now be reviewed, as it will be directly relevant to the experiment described in this chapter.

7.1.1 Symmetrical adaptation of saccades

Deubel, Wolf and Hauske (1986) and Deubel (1987) instructed human subjects and monkeys to track a target that jumped. During the saccadic response the target made a second jump (intra-saccadic step), either in the same direction as the original target, gain-increasing paradigm, or in the opposite direction, gain-decreasing paradigm. Their results showed that the size of the primary saccade adapted by increasing or decreasing respectively in as little as a few hundred trials. Adaptation occurred in an exponential manner being faster at the beginning of the experiment. Albano and King (1989) reported similar results using a different technique. They used a procedure that introduced a visuomotor mismatch between the retinal error signal (retinal distance between fovea and target image) and the motor error signal (movement required to accurately foveate the target). The saccadic system responded by modifying the amplitude of the saccade. This differs from an intra-saccadic step technique, as the mismatch applied is proportional to the amplitude of the saccade, effectively mimicking naturally occurring saccadic dysmetria for primary as well as corrective saccades. Saccade dysmetria was induced by electronically adding or subtracting 20% of the eye position signal to the target position. An example of this is shown in Figure 7.1. Addition to the target position was termed positive feedback and subtraction from the target position, negative feedback. The principle finding was that the adaptive mechanism was capable of producing rapid adjustments in saccade gain within 50 to 100 saccades over a matter of minutes. In many of the experiments up to 90% adaptation occurred within the first 50 saccades, hence measurable effects occurred within 5 minutes.

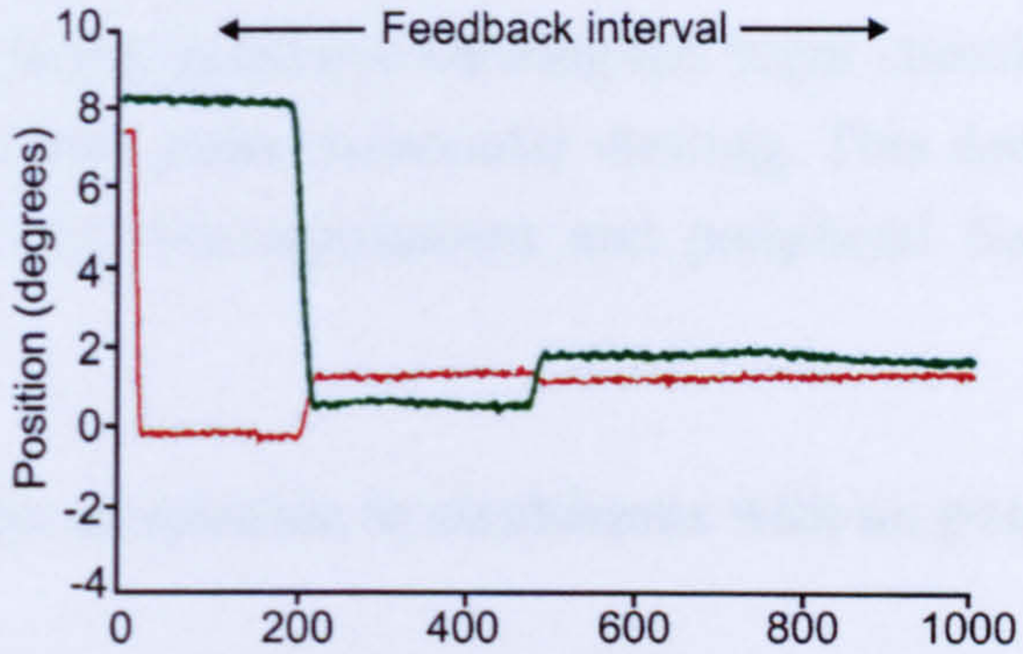


Figure 7.1: An example of an adaptation trial. Traces represent recorded horizontal target position (shown in red) and eye position (shown in green) of a monkey during an adaptation trial. During the feedback interval, a portion of the eye position signal was subtracted from the target's position by the computer. This is called a negative feedback condition, which mimics a form of dysmetria called hypermetria, resulting in a saccade that overshoots the target position. From Albano & King (1989).

7.1.2 Disconjugate adaptation in normal BSV

Saccades may also be adapted disconjugately, such that saccades become unequal in the two eyes. Lemij and Collewijn (1991) investigated the time course of disconjugate saccade adaptation using short term wear of anisometropic 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. Three subjects wore the glasses for varying periods from one to six hours. Saccade disconjugacy was then measured using magnetic sensor coils. They demonstrated in all three subjects that disconjugate saccades occurred with anisometropias ranging from 2DS to 8DS (dioptre spheres), with the adaptations almost complete within one hour. More recent studies (Kapoula, Eggert & Bucci, 1995; Van der Steen & Bruno, 1995) 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 indicated the presence of a fast learning mechanism.

7.1.3 Disconjugate adaptation in microtropia

As disconjugate adaptation sub-serves binocular vision, Kapoula, Bucci, Eggert and Zamfirescu (1996) questioned whether foveal fusion is a pre-requisite to achieve disconjugate adaptations. They studied three microstrabismic subjects who viewed a random dot pattern, which was 10% larger in one eye. They 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 to 10%. The induced 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.

7.1.4 Disconjugate adaptation in strabismus with no potential BSV

Bucci, Kapoula, Eggert and Garraud (1997) examined the degree of binocular vision necessary to stimulate disconjugate adaptation. Using the same experimental set-up as described above Kapoula Bucci, Eggert and Zamfirescu (1996) studied two subjects with small esotropia and peripheral fusion, two with intermediate esotropia, ARC and anomalous BSV and four subjects with large esotropia and no demonstrable binocular vision. The conclusions were that subjects with peripheral binocular vision, and those with anomalous BSV, were able to demonstrate disconjugate changes of 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, ranging from 2 to 22Δ. 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 to those normally stimulated without correction of the deviation. It may be that with their 'normal' ocular alignment, the disparity could be detected (possibly sub-cortically) and hence an appropriate disconjugate adaptation of saccades could be triggered. Correction of the angle of deviation was not done in the experiment described in this chapter.

Demonstration of disconjugate saccade adaptation, in subjects with strabismus and suppression, will show that despite lack of perception of the target in the strabismic eye

it is contributing to saccade programming. This will indicate that binocular vision is not required to stimulate disconjugate adaptation.

7.2 Experiment 9: Disconjugate saccade adaptation in binocular and strabismic subjects

7.2.1 Hypotheses

1. In subjects with BSV or strabismus with suppression there will be no difference in saccade disconjugacy at the end of an experimental test session compared to the beginning.
2. Using an electronic feedback system in one eye to induce disparity, subjects with normal BSV will show an increase in saccade disconjugacy, which will persist when the feedback is ceased.
3. Using an electronic feedback system in one eye to induce disparity, subjects with strabismus and suppression will demonstrate saccade disconjugacy appropriate in direction for the stimulus. Anomalous responses reported by Bucci, Kapoula, Eggert and Garraud (1997) will not be found, as the angle of strabismus will not be corrected in the present study.

7.3 Method

7.3.1 Participants

Fourteen adult subjects participated in this experiment, eight with normal bifoveal BSV and six with manifest strabismus. The group with normal BSV (none of whom have previously been reported) were all right eye dominant and had no ocular motility defects, their details are summarised in Table 7.1. The subjects with strabismus all had constant suppression and no clinically demonstrable BSV, their details are summarised in Table 7.2. Five of the six strabismic subjects were also included in the experiment in Chapter 6.

Subj	Gender	Age (yrs)	Refractive correction		Visual acuity		PCT	Stereo TNO	PFR
			RE	LE	RE	LE			
1	F	22	nil	nil	-0.10	-0.10	2Δ X	15''	40BO 18BI
2	F	23	nil	nil	-0.14	-0.12	4Δ X	30''	20BO 14BI
3	F	19	-1.25/ -1.00	-1.25/ -0.75	0.00	0.00	6Δ X	30''	25BO 10BI
4	F	21	nil	nil	-0.14	-0.16	2Δ X	30''	40BO 12BI
5	M	38	nil	nil	-0.10	-0.10	2Δ E	30''	40BO 14BI
6	F	46	-1.75/ -1.00	-1.25/ -0.50	0.00	0.00	2Δ E	30''	40BO 6BI
7	F	31	nil	nil	-0.04	-0.06	4Δ X	30''	25BO 8BI
8	M	34	-4.00/ -1.00	-3.00/ -0.50	-0.10	-0.10	6Δ X	15''	35BO 10BI

mean age 29.3 ±9.6

Table 7.1: Characteristics of subjects with normal BSV. PCT = prism cover test, TNO = TNO stereo test measured in seconds of arc, PFR = prism fusion range measured in prism dioptres, X = exophoria, E = esophoria.

Subj	Gender	Age (yrs)	Refractive correction		Visual acuity		Cover test	PCT
			RE	LE	RE	LE		
1	F	59	+2.25	+3.00/ +0.50	-0.10	0.20	Left ET	2ΔET
2	F	23	+6.50/-0.25	+5.50 *	-0.10	-0.20	Right ET	8ΔET
4	F	42	nil	nil	-0.10	0.00	Left XT	12ΔXT
5	F	40	nil	nil	0.40	-0.10	Right ET	18ΔET
6	F	21	+4.00	+5.00 *	-0.10	0.00	Left XT	18XT
9	F	19	+2.75	+3.00/-1.50	-0.10	0.60	Left XT	8ΔXT

mean age 34.0 ±15.7

Table 7.2: Characteristics of subjects with strabismus and suppression. All subjects, with the exception of subject 9, were also included in Experiment 3, Chapter 4 and Experiment 5, Chapter 6. The subject numbers used allow identification of the same subject throughout. Full clinical details are given in Appendix 5. ET = esotropia, XT = exotropia, PCT = prism cover test. * indicates subjects who wore contact lenses for the experiment.

7.3.2 Experimental set-up

Experiments were performed under dimmed ambient lighting conditions (2cd/m^2). The subjects were seated comfortably, in the laboratory set-up as shown in Figure 2.4, 114cm from the flat back projection screen. The subject's head was stabilised using the chin rest previously described, ensuring close fitting of cheek rests against the cheek bones and instructing the subject to remain firmly in position.

7.3.3 Stimuli

Projectors 1 and 2 projected identical sized targets consisting of a cross subtending 2° (see Chapter 5, Figure 5.2 for shape), luminance 18cd/m^2. These were projected so that they overlaid each other to appear as a single target and they could be moved by mirror galvanometers. The LCP shutters were set such that one target was visible to each eye. A blurred random dot stationary background (see Chapter 5, Figure 5.3) of luminance 4cd/m^2 was back projected by projector 3, and was constantly visible to both eyes.

The calibrated eye movement position signal could be scaled by a factor (the feedback gain) and used to move one of the targets. Feedback gain, calculated by dividing target velocity by eye velocity was selectively applied to one of the targets, visible to one eye only, to induce saccade disconjugacy. Feedback gain of +0.1 was used to move the target in the same direction as the eye. The electronic feedback system responded with a delay in the order of 10 to 15ms due to a combination of frequency response of the mirror galvanometer, computing time and sampling effects. A section of an eye movement plot is shown in Figure 7.2 where the delay between the eye and target movement can be seen.

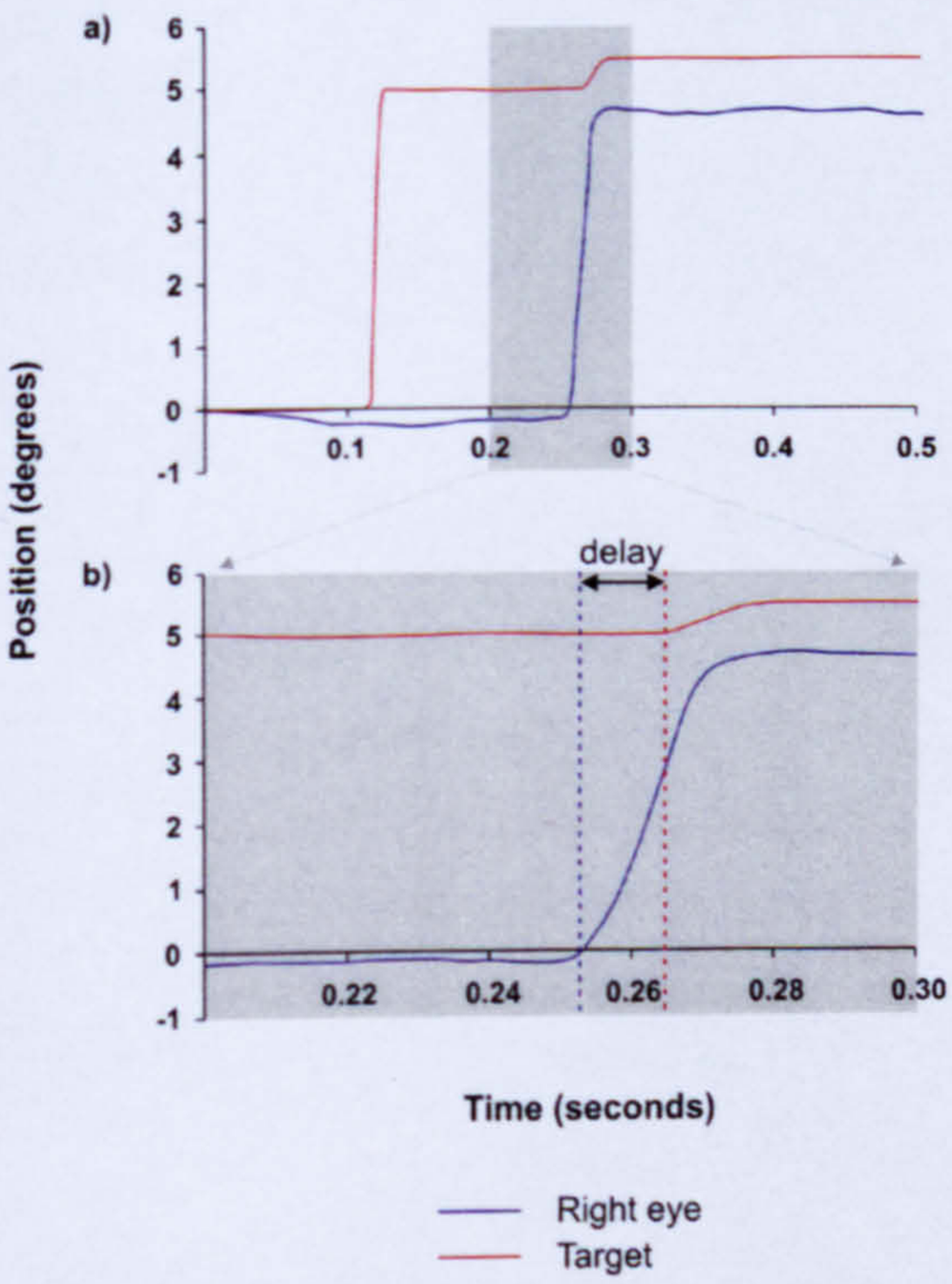


Figure 7.2: Eye movement trace of right eye and target position during feedback movement of the target. A feedback gain of +0.1 was applied to the target. As the eye moves the target moves in the same direction with a small time delay. a) shows a 0.5 second portion of the data, b) expands the shaded 0.1 second portion.

7.3.4 Design of the experiment

The experiment was performed in two groups of subjects: a group with normal BSV and a group with strabismus, normal retinal correspondence and suppression. Two experimental sessions were carried out in the BSV subjects and three for the strabismic subjects (see Table 7.3). Each experimental session had three phases: A pre-adaptation phase, an adaptation phase and a post-adaptation phase.

Feedback condition	Number of subjects	
	BSV group (n=8)	Strabismic group (n=6)
Feedback dominant eye	4	6
Feedback non-dominant eye	4	6
No feedback	8	6

Table 7.3: Number of subjects undergoing each feedback condition in subjects with BSV and subjects with constant strabismus and suppression.

The experiment was a repeated measures design, the independent variables were: feedback condition in the adaptation phase (feedback gain to the dominant eye, feedback gain to the non-dominant eye, or no feedback gain) and direction of the induced disparity (convergent or divergent). Table 7.4 gives further clarification of these. The dependent variable was the difference in saccade gain disconjugacy between the pre- and post-adaptation phases.

Saccades may become more accurate with practice to the same eccentricity or may fatigue over the duration of testing. Order effects were therefore counterbalanced by randomisation of the independent variables between subjects.

Eye receiving Feedback	Target direction	Induced disparity for centrifugal saccades	Induced disparity for centripetal saccades
Right eye	Leftward	Convergent	Divergent
Left eye	Rightward	Convergent	Divergent
None	Rightward or leftward	None	None

Table 7.4: Independent variables, eye receiving feedback, for BSV subjects feedback to the right eye was the dominant eye and left eye was the non-dominant eye. In strabismic subjects this depended on the individual subjects fixing eye. Convergent disparity is where the adducting eye is required to make a larger saccade than the abducting eye, divergent disparity is where the abducting eye is required to make larger saccades than the adducting eye.

7.3.5 Procedure

An information sheet detailing the experiment was given to all subjects prior to arrival in the laboratory. The procedure was outlined to them and they were encouraged to ask questions prior to giving consent to participate in the study.

Strabismic subjects attended three testing sessions and binocular subjects two testing sessions, each separated by a minimum of 24 hours and a maximum of one week. Each session consisted of three phases: the pre-adaptation phase (60 trials); the adaptation phase (210 trials), and the post adaptation phase (60 trials). Each phase was run in series directly after each other with no break.

All trials consisted of both targets initially making a 5° step in one direction from the central fixation point. The pre- and post-adaptation phases were the same in all experimental sessions and consisted of a single target step of 5° from the central fixation point and back. The same gaze direction and eccentricity was maintained for all trials in the session to facilitate fast adaptation. It has previously been shown that adaptation is induced according to direction of movement and it is slower if multiple eccentricities are used (Miller, Anstis & Templeton, 1981).

The adaptation phase consisted of two different conditions:

1. +0.1 feedback gain applied to the target visible to one eye.
2. A control condition in which there was no feedback applied.

The feedback gain of +0.1 and target amplitude of 5° were selected after a pilot study, which found that larger feedback gain led to subject awareness of target jitter, inability to maintain a single image of the target or movement of the target out of the recordable range due to the corrective saccade.

The eight subjects with normal BSV attended two sessions: one session where the feedback condition was performed and one session for the control condition. All subjects were right eye dominant, four had feedback applied to the dominant eye and four had feedback applied to the non-dominant eye. The six subjects with constant strabismus attended three sessions; feedback to the fixing eye, feedback to the strabismic eye and the control condition. The order of testing these conditions was randomised to balance order effect. When feedback was applied to the right eye,

saccades were made from the centre to the left and back, whilst when feedback was applied to the left eye, saccades were made from the centre to the right and back. This was to ensure that when convergent disparity was induced, saccades were always centrifugal and when divergent disparity was induced, saccades were always centripetal. This is due to the slight differences reported in centrifugal and centripetal saccades (Collewijn, Erkelens & Steinman, 1988). For subjects with normal BSV the same saccade direction was maintained for the control condition. In the strabismic group the saccade direction used when feedback was applied to the strabismic eye was also used in the control condition.

Subjects were instructed to look at the centre of the target cross and move their eyes to follow it at all times as quickly and accurately as possible. They were told not to move their eyes until they actually saw the target appear in the eccentric position. They were also asked to try to keep the target single and clear at all times. The subject was informed of the gaze direction prior to commencing the experimental session. Each experimental session lasted approximately 30 minutes. Calibration of eye movements was performed prior to each phase.

The two identical overlapping targets, presented to each eye separately using the LCP shutters, appeared in the centre of the screen and, after a randomised time delay (500 - 1500ms), jumped 5° to the right or left of centre. Following a randomised period (500 - 1500ms) the targets would both return to the centre. In the adaptation phase of the feedback condition, both targets jumped from the centre to 5° eccentricity. When the eye with feedback moved to fixate the target, the dissociated target visible to that eye only moved in the direction of the eye movement by a feedback gain of +0.1 producing retinal disparity. This therefore created a stimulus to induce disconjugate saccade adaptation.

Eye movements were recorded using the method described in Chapter 2. The pre- and post-adaptation phases were performed with monocular viewing by closing the LCP shutter in front of the non-preferred eye. This was to prevent binocular information in the post-adaptation phase reducing any increased disconjugacy that may have occurred during the adaptation phase. Viewing was binocular during the adaptation phase.

Following the experiment, the subjects were asked whether the target ever appeared double or whether they appreciated depth to the target in relation to the background. None of the subjects in either group reported diplopia during any of the test sessions.

All of the BSV group was aware of depth of the target compared to the background in the feedback conditions but not in the no feedback condition. None of the strabismic group was aware of depth in any of the conditions.

7.4 Results

Saccadic eye movement data was analysed as outlined in Chapter 2. Each saccade was checked visually to confirm correct detection of the primary saccade. Saccades with latency <80ms were excluded as they were considered to be anticipatory (Fischer & Weber, 1993) and saccades with latency >450ms were excluded as they were not considered to be visually triggered (Walker, Deubel, Schneider & Findlay, 1997). In all subjects a small number of saccades could not be analysed due to blinks or incorrect fixation. This ranged from 8% to 22% with a mean of 12% excluded from the analysis.

Mean saccade gain for each eye was calculated for the pre- and post-adaptation phase for each of the feedback conditions. The gain of the eye without feedback applied was subtracted from the gain of the eye with feedback applied, to give the saccade gain disconjugacy. This was so that any change in disconjugacy to compensate for the induced disparity (adaptation) would be represented by an increasing positive value in all cases. The magnitude of the adaptive effect was taken as the change in mean gain disconjugacy during the pre- and post-adaptation phases.

7.4.1 Subjects with normal BSV

The mean gain of saccades in each eye, and saccade disconjugacy in the pre- and post-adaptation phases, are presented for all eight subjects in Table 7.5a (convergent disparity) and Table 7.6b (divergent disparity). Subjects 1 to 4 had feedback to the dominant right eye during the adaptation phase and subjects 5 to 8 had feedback to the non-dominant left eye. Tables 7.5b and 7.6b show the same information for the no feedback condition for saccades made in the same direction as Tables 7.5a and 7.6a respectively. The magnitude of any adaptation effect is also shown in these tables where positive values represent adaptation in the correct direction to compensate for the disconjugacy.

Figure 7.3 shows the pooled mean saccade gain disconjugacy for the group (all 8 subjects) in the pre- and post-adaptation phases.

Normal BSV Group

a) Feedback condition – convergent disparity (centrifugal saccades)

Subject	Pre-adaptation phase			Post-adaptation phase			Magnitude of adaptation
	Gain FB	Gain no FB	Disconjugacy	Gain FB	Gain no FB	Disconjugacy	
1	1.043	1.054	-0.011	1.143	1.064	0.080	0.091
2	1.055	1.085	-0.030	1.051	0.974	0.076	0.106
3	1.034	1.002	0.032	1.013	0.842	0.171	0.139
4	0.922	0.844	0.078	1.083	0.859	0.223	0.145
5	0.993	0.978	0.015	1.169	0.857	0.312	0.297
6	0.943	0.965	-0.022	1.003	0.833	0.170	0.192
7	0.948	0.978	-0.029	1.003	0.916	0.086	0.116
8	1.208	1.199	0.009	1.170	1.084	0.086	0.077
Mean	**1.018**	**1.013**	**0.005**	**1.079**	**0.929**	**0.151****	**0.145**
SD	**0.091**	**0.103**	**0.037**	**0.073**	**0.101**	**0.085**	**0.071**
SE	**0.032**	**0.037**	**0.013**	**0.026**	**0.036**	**0.030**	**0.025**

b) No feedback condition (centrifugal saccades)

Subject	Pre-adaptation phase			Post-adaptation phase			Magnitude of adaptation
	Gain FB	Gain no FB	Disconjugacy	Gain FB	Gain no FB	Disconjugacy	
1	1.095	1.112	-0.017	1.093	1.083	0.010	0.027
2	1.080	1.112	-0.032	1.012	1.022	-0.009	0.023
3	1.057	1.017	0.040	1.010	0.963	0.047	0.007
4	1.080	0.974	0.106	1.006	0.900	0.107	0.001
5	1.026	1.015	0.010	1.033	1.020	0.013	0.003
6	1.005	1.043	-0.038	0.952	0.986	-0.034	0.005
7	0.937	1.001	-0.065	0.923	0.983	-0.061	0.004
8	1.166	1.155	0.011	1.100	1.084	0.016	0.005
Mean	**1.056**	**1.054**	**0.002**	**1.016**	**1.005**	**0.011**	**0.009**
SD	**0.068**	**0.064**	**0.053**	**0.061**	**0.062**	**0.051**	**0.010**
SE	**0.024**	**0.023**	**0.019**	**0.022**	**0.022**	**0.018**	**0.003**

Table 7.5: Mean saccade gain for each eye and saccade gain disconjugacy to 5° target eccentricity in the pre- and post-adaptation phases. **a)** results for feedback condition where **convergent disparity** was induced in the adaptation phase; **b)** in the **no feedback control condition,** no disparity was induced in the adaptation phase. Subjects 1-4 (shaded section) had feedback applied to the dominant (right) eye and hence made saccades from centre to left and back to centre, subjects 5-8 had feedback applied to the non-dominant (left) eye and made saccades from centre to right and back to centre. The different gaze directions were used so that convergent disparity was always induced with centrifugal saccades and divergent disparity centripetal saccades. The same saccade direction was maintained for the no feedback condition results shown in b. Saccade disconjugacy was calculated by subtracting the gain of the eye without feedback (gain no FB) from the eye undergoing feedback (gain FB). This was to produce relative positive values if adaptation occurred. The same eye gains were subtracted in the no feedback condition. ** represents a statistically significant change between pre- and post-adaptation phases of the disconjugacy, paired samples t-test $p<0.01$. SD = standard deviation, SE = standard error.

Normal BSV Group

a) Feedback condition – divergent disparity (centripetal saccades)

Subj	Pre-adaptation phase			Post-adaptation phase			Magnitude of adaptation
	Gain FB	Gain no FB	Disconjugacy	Gain FB	Gain no FB	Disconjugacy	
1	1.053	0.994	0.059	1.173	1.053	0.120	0.060
2	1.068	1.021	0.047	1.175	0.961	0.214	0.166
3	0.938	0.955	-0.018	0.975	0.857	0.118	0.135
4	0.984	1.043	-0.059	1.126	1.004	0.123	0.182
5	1.019	0.969	0.050	1.244	0.889	0.355	0.305
6	1.032	0.975	0.057	1.053	0.933	0.120	0.063
7	1.076	1.014	0.062	0.993	0.885	0.108	0.046
8	1.237	1.112	0.125	1.116	0.886	0.230	0.105
Mean	**1.051**	**1.010**	**0.040**	**1.107**	**0.933**	**0.173****	**0.133**
SD	**0.088**	**0.050**	**0.056**	**0.094**	**0.068**	**0.088**	**0.086**
SE	**0.031**	**0.018**	**0.020**	**0.033**	**0.024**	**0.031**	**0.030**

b) No feedback condition (centripetal saccades)

Subj	Pre-adaptation phase			Post-adaptation phase			Magnitude of adaptation
	Gain FB	Gain no FB	Disconjugacy	Gain FB	Gain no FB	Disconjugacy	
1	1.094	1.032	0.062	1.079	1.041	0.038	-0.024
2	1.104	1.067	0.037	1.058	0.997	0.061	0.024
3	0.909	0.944	-0.035	0.966	1.008	-0.042	-0.006
4	0.965	1.019	-0.054	0.901	0.938	-0.037	0.018
5	1.048	1.003	0.045	1.048	1.002	0.046	0.001
6	1.005	0.985	0.020	0.961	0.925	0.036	0.016
7	1.002	0.927	0.075	1.006	0.932	0.074	-0.001
8	1.167	1.062	0.105	1.096	1.012	0.083	-0.022
Mean	**1.037**	**1.005**	**0.032**	**1.014**	**0.982**	**0.032**	**0.001**
SD	**0.083**	**0.051**	**0.054**	**0.067**	**0.044**	**0.047**	**0.018**
SE	**0.029**	**0.018**	**0.019**	**0.024**	**0.015**	**0.017**	**0.006**

Table 7.6: Mean saccade gain for each eye and saccade gain disconjugacy to 5° target eccentricity in the pre- and post-adaptation phases. **a)** results for feedback condition where **divergent disparity** was induced in the adaptation phase; **b)** in the **no feedback control condition,** no disparity was induced in the adaptation phase. Subjects 1-4 (shaded section) had feedback applied to the dominant (right) eye and hence made saccades from centre to left and back to centre, subjects 5-8 had feedback applied to the non-dominant (left) eye and made saccades from centre to right and back to centre. The different gaze directions were used so that convergent disparity was always induced with centrifugal saccades and divergent disparity centripetal saccades. The same saccade direction was maintained for the no feedback condition results shown in b. Saccade disconjugacy was calculated by subtracting the gain of the eye without feedback (gain no FB) from the eye undergoing feedback (gain FB). This was to produce relative positive values if adaptation occurred. The same eye gains were subtracted in the no feedback condition. ** represents a statistically significant change between pre- and post-adaptation phases of the disconjugacy, paired samples t-test $p<0.01$. SD = standard deviation, SE = standard error.

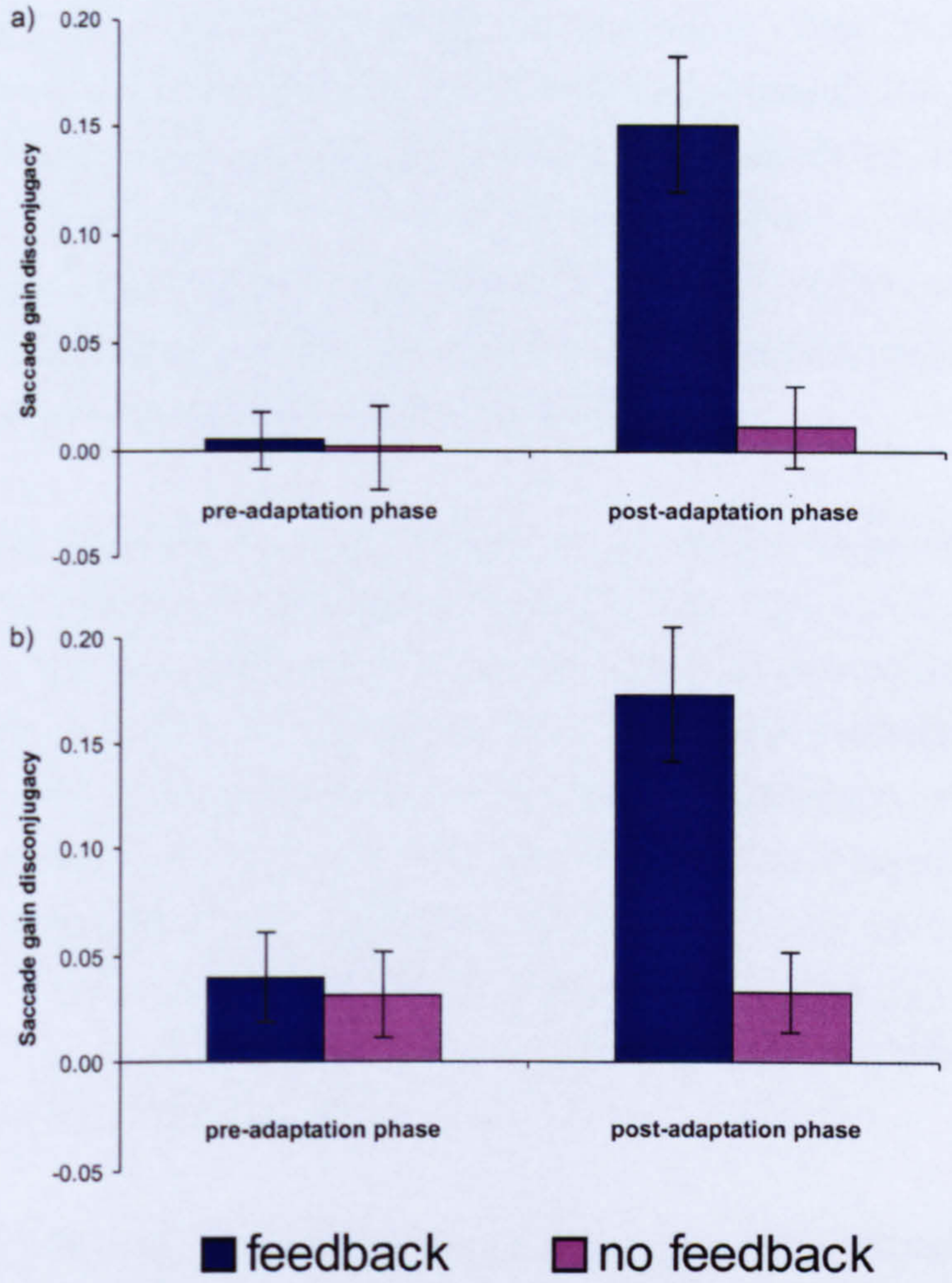


Figure 7.3: Mean saccade gain disconjugacy, pooled data for the normal BSV group (n=8) a) convergent disparity; b) divergent disparity. Error bars = ±1standard error.

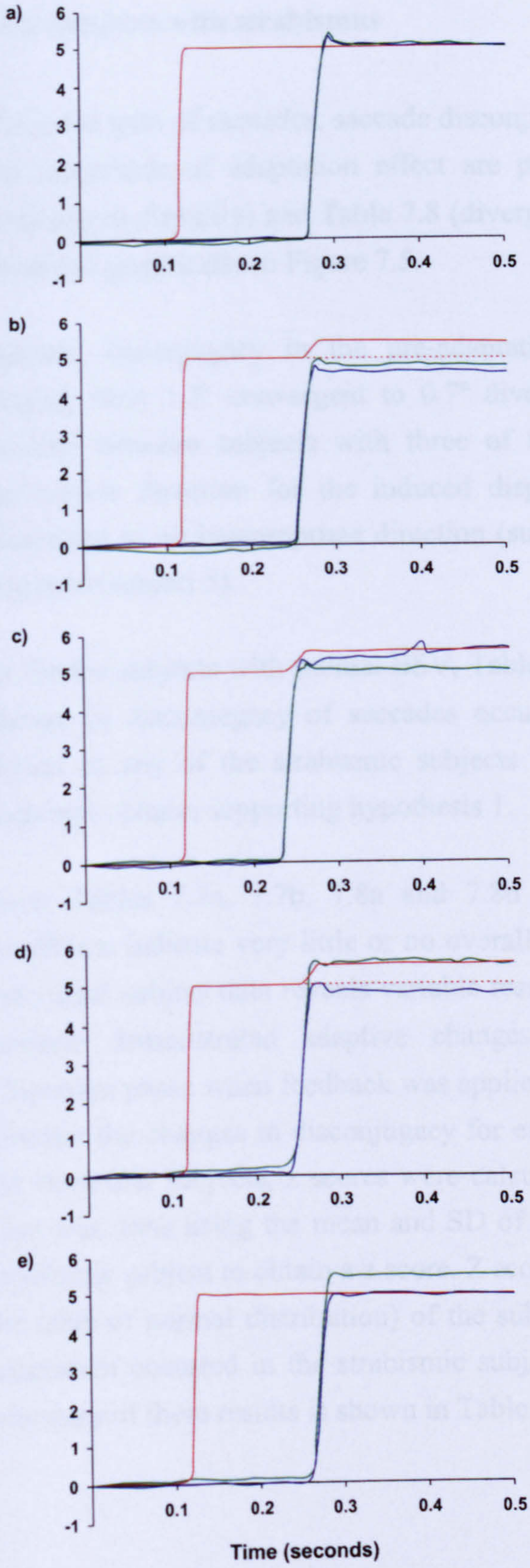
From Tables 7.5b and 7.6b it is evident that when no feedback was applied during the adaptation phase there was no change in saccade gain disconjugacy between the pre- and post-adaptation phases in any of the subjects. The mean change in gain disconjugacy for the group was just 0.009 ±0.003 for centrifugal saccades and 0.001 ±0.018 for centripetal saccades.

Tables 7.5a and 7.6a show that using feedback gain to one eye in this experimental set-up all subjects demonstrated adaptive changes to saccades producing increased disconjugacy following the adaptation phase when feedback was applied to the target visible to one eye. The disconjugacy produced was appropriate in direction for the induced disparity for all subjects. The mean change in gain disconjugacy for the group was just 0.145 ±0.071 for centrifugal saccades (convergent disparity) and 0.133 ±0.086 for centripetal saccades (divergent disparity). A typical example of the eye movement response is shown in Figure 7.4.

When no feedback was applied during the adaptation phase there was no change in disconjugacy of saccades between the pre- and post-adaptation phases in any of the subjects. A paired t-test showed that there was no significant difference (centrifugal saccades, $t = -0.967$, $df = 7$, $p>0.05$; centripetal saccades, $t = -0.079$, $df = 7$, $p>0.05$). Details of the t-tests are shown in Appendix 11.1.1. This control condition indicates that there are no changes in disconjugacy due to non-adaptational processes over the course of the thirty minute experiment supporting hypothesis 1.

For convergent disparity the mean change in disconjugacy following adaptation for the subjects with feedback to the dominant eye (subjects 1-4) was 0.120 ±0.026 and non-dominant eye (subjects 5-8) was 0.170 ±0.097. For divergent disparity the mean change in disconjugacy following adaptation for the subjects with feedback to the dominant eye (subjects 1-4) was 0.136 ±0.054 and non-dominant eye (subjects 5-8) was 0.130 ±0.119. There was no significant difference between feedback to the dominant or non-dominant eye (unpaired samples t-test, convergent disparity, $t = 1.002$, $df = 6$, $p>0.05$; divergent disparity, $t = -0.092$, $df = 6$, $p>0.05$). Statistical details are shown in Appendix 11.1.2. The data in the two feedback conditions (dominant eye and non-dominant eye) was therefore pooled for further analysis and as shown in Figure 7.3.

A statistical difference in disconjugacy between pre- and post-adaptation phases was found for both convergent and divergent induced disparity (paired samples t-test; convergent disparity, $t = -5{,}784$, $df = 7$, $p<0.001$; divergent disparity, $t = -4.386$, $df = 7$, $p<0.01$). This supports hypothesis 2, which proposed that with feedback to one eye, subjects with normal BSV would show an increase in saccade disconjugacy, which will persist when the feedback is ceased. The effect of feedback inducing a convergent or divergent disparity was not significantly different (paired samples t-test, $t=0.574$, $df = 7$, $p>0.05$) (see Appendix 11.1.2).



Pre- adaptation phase
Both superimposed targets (shown in red) move from the centre of the screen to 5° right. Both eyes make a saccade very slightly overshooting the target.

Early adaptation phase 1
Both superimposed targets move from the centre of the screen to 5° right. Both eyes make a saccade to the right but as the left eye moves (shown in green) the target seen by the left eye receives +0.1 feedback. The target seen by the right eye (dotted red line) remains at 5°. In this early stage it is apparent that the saccades have become slightly disconjugate with the left eye moving slightly more than the right eye (shown in blue).

Early adaptation phase 2
A second example from early in the adaptation period is shown. The primary saccade in the left eye is very slightly larger than the right eye. The left eye then gradually moves on to target.

Late adaptation phase
Disconjugate (convergent) primary saccade, LE>RE

Post-adaptation phase
Both superimposed targets move from the centre of the screen to 5° right and remain at this eccentricity (as in the pre-adaptation phase). The left eye continues to make a larger saccade due to saccade adaptation.

Figure 7.4: A typical example of saccadic eye movements recorded in the three experimental phases. Data from subject 5 with normal BSV.

7.4.2 Subjects with strabismus

The mean gain of saccades, saccade disconjugacy in the pre- and post-adaptation phases and magnitude of adaptation effect are presented for all six subjects in Table 7.7 (convergent disparity) and Table 7.8 (divergent disparity). Individual subject results are presented graphically in Figure 7.5.

Saccade disconjugacy in the pre-adaptation phase was variable between subjects ranging from 1.3° convergent to 0.7° divergent. The response to feedback was also variable between subjects with three of the six subjects showing adaptation in an appropriate direction for the induced disparity (subjects 2, 4 and 9), two showing adaptation in an inappropriate direction (subjects 1 and 6), and one having no obvious response (subject 5).

As for the subjects with normal BSV, Tables 7.7c and 7.8c and Figure 7.5 show that no change in disconjugacy of saccades occurred between the pre- and post-adaptation phases in any of the strabismic subjects when no feedback was applied during the adaptation phase, supporting hypothesis 1.

From Tables 7.7a, 7.7b, 7.8a and 7.8b the group mean results for the feedback conditions indicate very little or no overall adaptation effects, however examination of individual subject data reveals variable results (as shown in Figure 7.5). Five of the six subjects demonstrated adaptive changes to saccade disconjugacy following the adaptation phase when feedback was applied to a target visible to one eye. To determine whether the changes in disconjugacy for each subject were significantly different from the binocular subjects, z scores were calculated and levels of significance determined. This was done using the mean and SD of the BSV group and the mean result of each strabismic subject to obtain a z score. Z scores were then converted to probability (using the table of normal distribution) of the subject being different from the BSV group. If adaptation occurred in the strabismic subject the p value would be non-significant. A summary of these results is shown in Table 7.9 and full details are in Appendix 11.2.

Strabismic Group

a) Feedback fixing eye

Subject	Pre-adaptation Phase			Post-adaptation Phase			Magnitude of adaptation
	Fix	Strab	Disconjugacy	Fix	Strab	Disconjugacy	
1	1.152	1.373	-0.221	1.064	1.415	-0.351	-0.130
2	1.014	0.956	0.058	1.114	0.893	0.222	0.163
4	1.018	0.940	0.078	1.249	1.050	0.199	0.120
5	0.753	0.865	-0.112	0.675	0.739	-0.064	0.048
6	0.998	1.085	-0.087	0.755	1.164	-0.409	-0.322
9	0.982	0.848	0.134	1.017	0.788	0.229	0.095
MEAN	**0.986**	**1.011**	**-0.025**	**0.979**	**1.008**	**-0.029**	**-0.004**
SD	**0.129**	**0.196**	**0.136**	**0.220**	**0.255**	**0.293**	**0.186**
SE	**0.053**	**0.080**	**0.056**	**0.090**	**0.104**	**0.120**	**0.076**

b) Feedback strabismic eye

Subject	Pre-adaptation Phase			Post-adaptation Phase			Magnitude of adaptation
	Fix	Strab	Disconjugacy	Fix	Strab	Disconjugacy	
1	1.056	1.281	0.225	1.015	0.896	-0.119	-0.314
2	1.038	1.098	0.060	1.067	1.173	0.105	0.045
4	0.933	0.812	-0.121	0.918	1.055	0.136	0.258
5	0.936	1.112	0.176	0.927	1.043	0.116	-0.060
6	0.902	1.001	0.099	0.753	0.888	0.134	0.035
9	0.928	1.086	0.158	0.800	1.408	0.608	0.450
MEAN	**0.840**	**0.915**	**0.082**	**0.791**	**0.927**	**0.157**	**0.096**
SD	**0.319**	**0.352**	**0.109**	**0.301**	**0.373**	**0.169**	**0.218**
SE	**0.130**	**0.144**	**0.044**	**0.123**	**0.152**	**0.069**	**0.089**

c) No feedback condition

Subject	Pre-adaptation Phase			Post-adaptation Phase			Magnitude of adaptation
	Fix	Strab	Disconjugacy	Fix	Strab	Disconjugacy	
1	0.909	1.146	0.237	0.930	1.123	0.193	-0.044
2	1.055	1.149	0.094	1.090	1.188	0.098	0.004
4	0.876	0.713	-0.163	1.023	0.833	-0.191	-0.028
5	0.984	1.314	0.330	1.111	1.448	0.337	0.006
6	0.980	1.056	0.076	0.960	1.103	0.144	0.068
9	0.936	1.034	0.098	0.894	1.005	0.111	0.014
MEAN	**0.844**	**0.916**	**0.082**	**0.869**	**0.947**	**0.090**	**0.003**
SD	**0.324**	**0.365**	**0.136**	**0.334**	**0.382**	**0.130**	**0.039**
SE	**0.132**	**0.149**	**0.056**	**0.136**	**0.156**	**0.053**	**0.016**

Table 7.7: Mean saccade gain for each eye, saccade gain disconjugacy and difference in saccade gain disconjugacy between the pre and post-adaptation phases for each subject following induced convergent disparity. Fix = fixing eye, Strab = strabismic eye. The fixing eye was the right eye in subjects 1, 4, 6 and 9 and left eye in subjects 2 and 5. Saccade gain disconjugacy was calculated by subtracting eye without feedback from eye with feedback, i.e. increased positive values would be expected in the post-adaptation phase if adaptation occurred. Where no feedback was applied (c) gain of the fixing eye was subtracted from gain of the strabismic eye. SD = standard deviation, SE = standard error.

Strabismic Group

a) Feedback fixing eye

Subject	Pre-adaptation Phase			Post-adaptation Phase			Magnitude of adaptation
	Fix	Strab	Disconjugacy	Fix	Strab	Disconjugacy	
1	1.054	1.334	-0.280	1.007	1.486	-0.479	-0.199
2	0.994	1.051	-0.056	1.158	0.989	0.170	0.226
4	0.972	1.021	-0.049	1.179	0.983	0.196	0.245
5	0.881	1.074	-0.193	0.590	0.759	-0.169	0.024
6	0.987	1.055	-0.069	0.748	0.946	-0.198	-0.129
9	1.003	0.952	0.051	1.070	0.898	0.172	0.122
MEAN	**0.982**	**1.081**	**-0.099**	**0.959**	**1.010**	**-0.051**	**0.048**
SD	**0.057**	**0.131**	**0.118**	**0.238**	**0.248**	**0.275**	**0.184**
SE	**0.023**	**0.054**	**0.048**	**0.097**	**0.101**	**0.112**	**0.075**

b) Feedback strabismic eye

Subject	Pre-adaptation Phase			Post-adaptation Phase			Magnitude of adaptation
	Fix	Strab	Disconjugacy	Fix	Strab	Disconjugacy	
1	1.106	1.351	0.245	1.012	0.943	-0.069	-0.343
2	0.987	0.955	-0.032	0.965	1.154	0.190	0.221
4	0.908	0.971	0.063	0.904	1.061	0.157	0.094
5	0.773	0.883	0.110	0.976	1.122	0.147	0.037
6	0.916	1.035	0.119	0.546	0.930	0.384	0.265
9	1.011	0.886	-0.124	0.862	1.058	0.197	0.321
MEAN	**0.950**	**1.014**	**0.063**	**0.878**	**1.045**	**0.167**	**0.099**
SD	**0.113**	**0.175**	**0.129**	**0.171**	**0.092**	**0.145**	**0.242**
SE	**0.046**	**0.071**	**0.053**	**0.070**	**0.037**	**0.059**	**0.099**

c) No feedback condition

Subject	Pre-adaptation Phase			Post-adaptation Phase			Magnitude of adaptation
	Fix	Strab	Disconjugacy	Fix	Strab	Disconjugacy	
1	0.952	1.192	0.240	0.904	1.118	0.214	-0.026
2	1.070	1.002	-0.069	1.174	1.128	-0.046	0.023
4	0.812	0.882	0.070	0.947	1.004	0.056	-0.014
5	0.981	1.094	0.113	0.981	1.163	0.182	0.069
6	0.980	1.093	0.113	0.902	1.004	0.102	-0.012
9	1.026	0.864	-0.162	0.990	0.891	-0.099	0.064
MEAN	**0.970**	**1.021**	**0.051**	**0.983**	**1.052**	**0.068**	**0.017**
SD	**0.088**	**0.130**	**0.144**	**0.101**	**0.103**	**0.124**	**0.041**
SE	**0.036**	**0.053**	**0.059**	**0.041**	**0.042**	**0.050**	**0.017**

Table 7.8: Mean saccade gain for each eye, saccade gain disconjugacy and difference in saccade gain disconjugacy between the post and pre-adaptation phases for each subject following induced divergent disparity. Fix = fixing eye; Strab = strabismic eye. The fixing eye was the right eye in subjects 1, 4, 6 and 9 and left eye in subjects 2 and 5. Saccade gain disconjugacy was calculated by subtracting eye without feedback from eye with feedback, such that increased positive values would be expected in the post-adaptation phase if adaptation occurred. Where no feedback is applied (c) gain of the fixing eye was subtracted from gain of the strabismic eye. SD = standard deviation, SE = standard error.

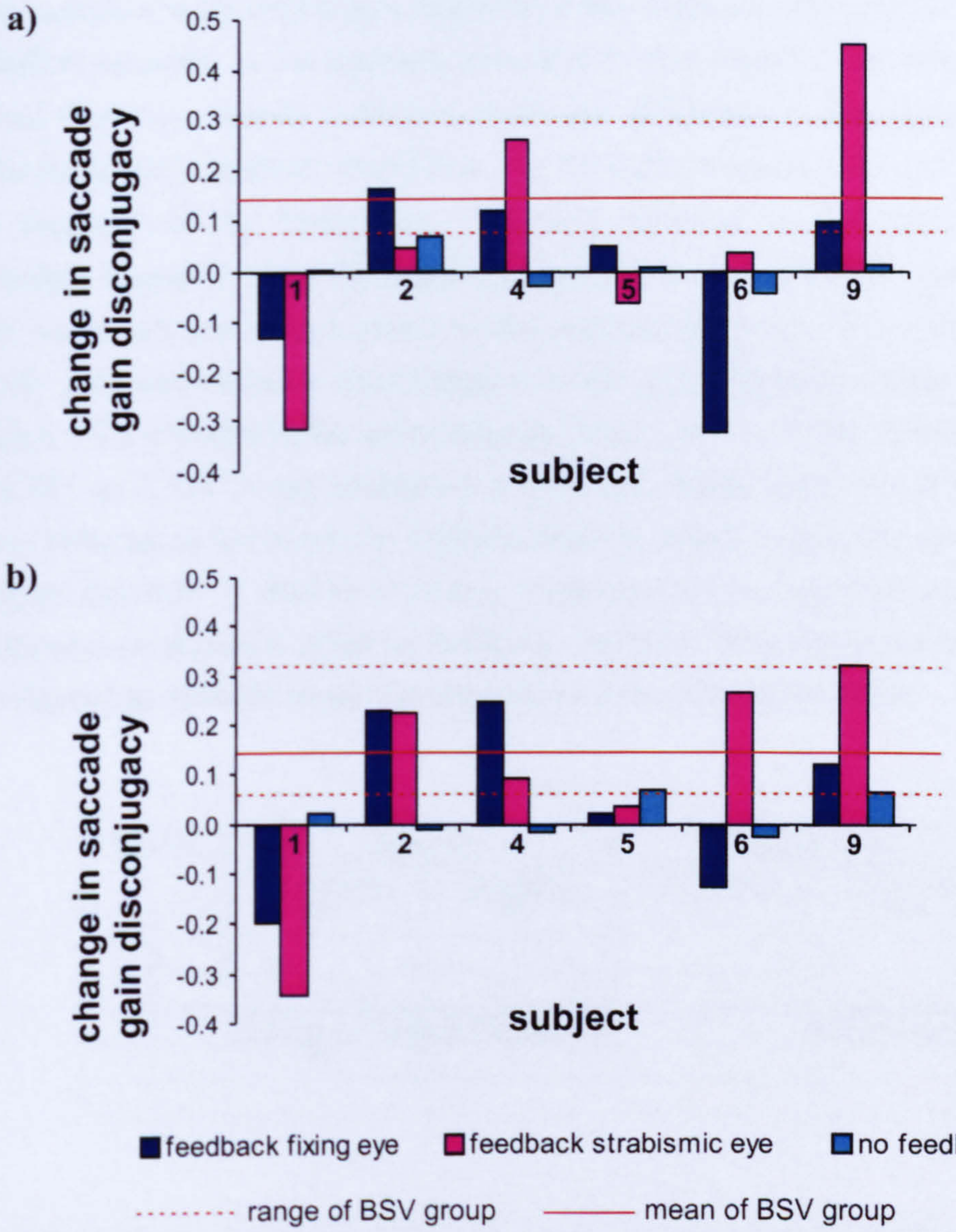


Figure 7.5: Magnitude of disconjugate saccade gain adaptation in strabismic subjects following adaptation period. a) convergent disparity (centrifugal saccades), b) divergent disparity (centripetal saccades).

Three subjects (subjects 2, 4 and 9) demonstrated adaptation in a direction appropriate to the induced disparity for all conditions (feedback fixing eye and strabismic eye for convergent and divergent disparity). The response from subject 9, although appropriate in direction, was significantly larger than the binocular subjects when feedback was introduced to the strabismic eye ($p<0.01$, see Table 7.7 and Appendix 11.2). Subject 1 demonstrated adaptation in the opposite direction to that required for compensation of the induced disparity in all conditions where feedback was applied in the adaptation phase. Subject 6 demonstrated a mixed response; when feedback was applied to the strabismic eye adaptation occurred in the appropriate direction for divergent disparity

and no adaptation for convergent disparity; when feedback was applied to the fixing eye adaptation occurred in the opposite direction to that required for compensation of the induced disparity. Subject 5 did not show any difference in disconjugacy between the no feedback and feedback conditions for divergent disparity or convergent disparity with feedback to the fixing eye. The only response in this subject occurred for convergent disparity when feedback was applied to the strabismic eye, the adaptation effect was small and inappropriate to the induced disparity. This subject had variable saccade gain and variable disconjugacy in the pre-adaptation phase between testing sessions, with pre-adaptation gains ranging from 0.753 to 0.984 in the fixing (left) eye and 0.865 to 1.314 in the strabismic (right) eye. From Table 7.9 it appears that this subject behaved as the binocular subjects when feedback was in the strabismic eye with divergent disparity. It should be noted, however, that the apparent adaptation in these conditions was also seen in the no feedback condition. It therefore can be concluded that this subject had variable responses and had no clear adaptation effect.

Subject	Fixing eye		Strabismic eye	
	Convergent	Divergent	Convergent	Divergent
1	***	***	***	***
2	-	-	-	-
4	-	-	-	-
5	-	-	**	-
6	***	**	-	-
9	-	-	***	*

Table 7.9: Summary of significance levels of z scores for individual strabismic subjects. Conditions where the results were significantly different from the BSV group are represented as follows: * = $p < 0.05$; ** = $p < 0.01$; *** = $p < 0.001$. Where there is no significant difference from the BSV group the symbol - is used. Results in red indicate adaptation occurring in an appropriate direction to the induced disparity and those in black indicate adaptation occurring in an inappropriate direction to the induced disparity. The shaded cells for subject 5 represent results that although were not significantly different from the BSV group, were the equivalent to the response in this subject in the no feedback condition, hence this subject did not show a difference in the feedback condition compared to the no feedback condition.

7.4.3 Time course of saccade adaptation

To identify any differences in the response between the subjects with normal BSV and subjects with strabismus the adaptation phase was examined further. Figure 7.6 and 7.7 show the mean saccade gain disconjugacy over the time course of the three experimental phases, with feedback applied to the dominant eye (Figure 7.6) and to the non-dominant eye (Figure 7.7). The figures are pooled data of three BSV subjects, who

demonstrated similar adaptation patterns (see individual subject data shown in Appendix 12.1) and three strabismic subjects who adapted in the appropriate direction for the induced disparity (see individual subject data shown in Appendix 12.2). The mean disconjugacy and standard error for each run (15 saccades) is plotted.

From Figures 7.6 and 7.7 the time course of adaptation appeared similar in all subjects within each group. A small amount of disconjugacy was present in the pre-adaptation phase, which was fairly consistent for the four runs. The largest increase in disconjugacy occurred in subjects with normal BSV, during the first five to seven runs of the adaptation phase (approximately five minutes). Adaptation reached a maximum level and then a plateau in the effect was seen in the BSV subjects. A similar effect was seen in the strabismic subjects. In both groups of subjects the increased disconjugacy persisted during the post-adaptation phase in the absence of feedback to one eye. The disconjugacy reduced gradually over the four runs of the post-adaptation phase.

Four separate two-factor repeated measures trend analyses (Winer, 1962) were performed on the data of the adaptation phase to determine whether there was a difference between the time course of adaptation for convergent and divergent disparity in each group. These are described fully in Appendix 12.3 and details shown in Appendix 12.4.1. They revealed that there were no significant differences between the time course of adaptation for convergent and divergent disparity, such that for example, the data shown in Figure 7.6a was not significantly different from Figure 7.6b and Figure 7.6c was not significantly different from Figure 7.6d.

Four separate two-factor mixed measures trend analyses were performed on the data to determine whether there was a difference in the adaptation phases between the two groups with feedback to the dominant and non-dominant eye for convergent and divergent disparity. These are described fully in Appendix 12.3 and details shown in Appendix 12.4.2. They revealed that there were no significant differences between the time course of adaptation for BSV subjects and strabismic subjects, such that for example, the data shown in Figure 7.6a was not significantly different from Figure 7.6c and Figure 7.6b was not significantly different from Figure 7.6d.

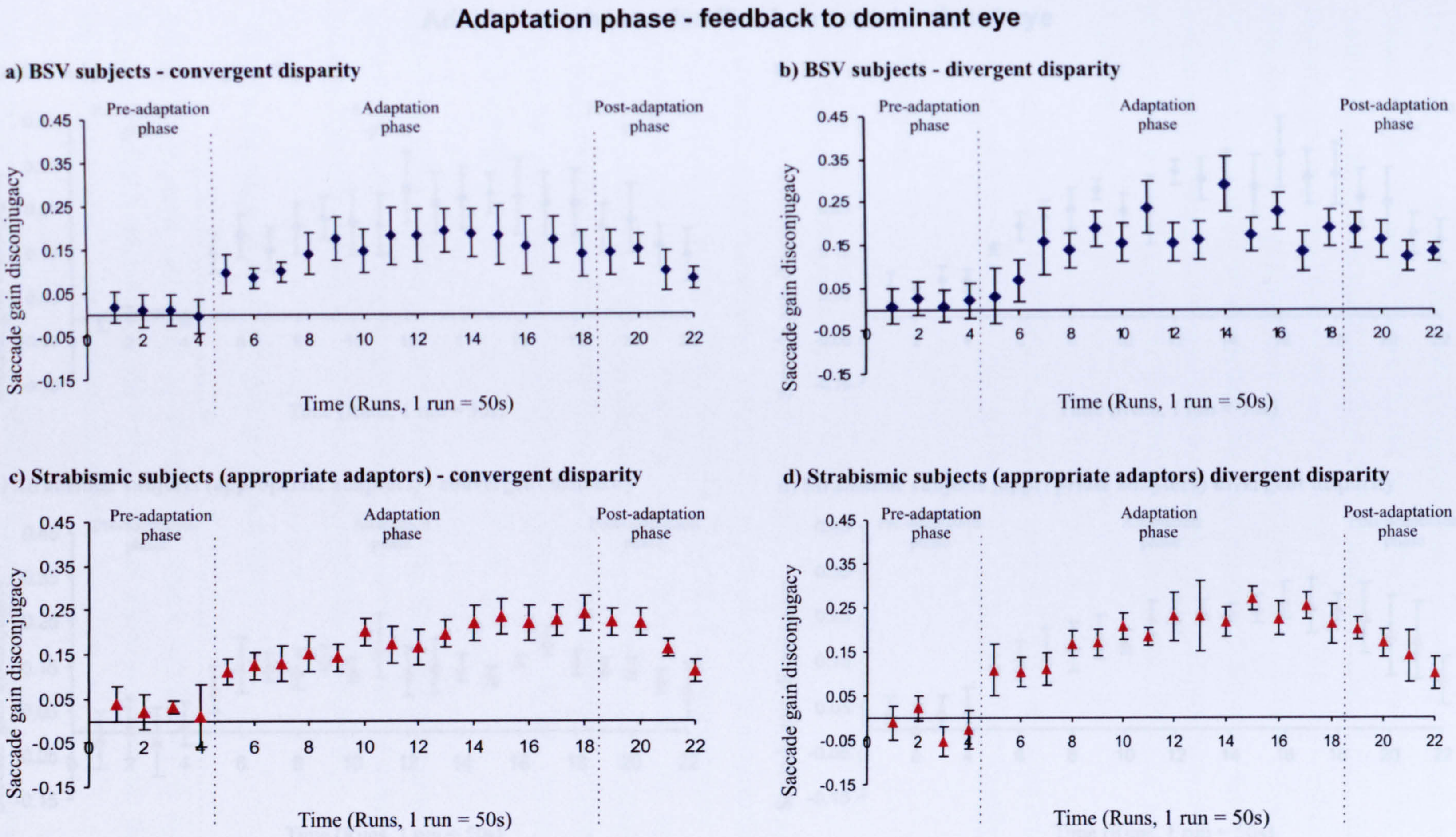


Figure 7.6: Mean saccade gain disconjugacy over the time course of the three experimental phases for BSV subjects (1, 2 & 4) and strabismic subjects (2, 4 & 9). Pooled data of three BSV subjects who received feedback to the dominant eye and three strabismic subjects who demonstrated appropriate disconjugate adaptation with feedback to the fixing eye. Error bars represent +/- 1SE.

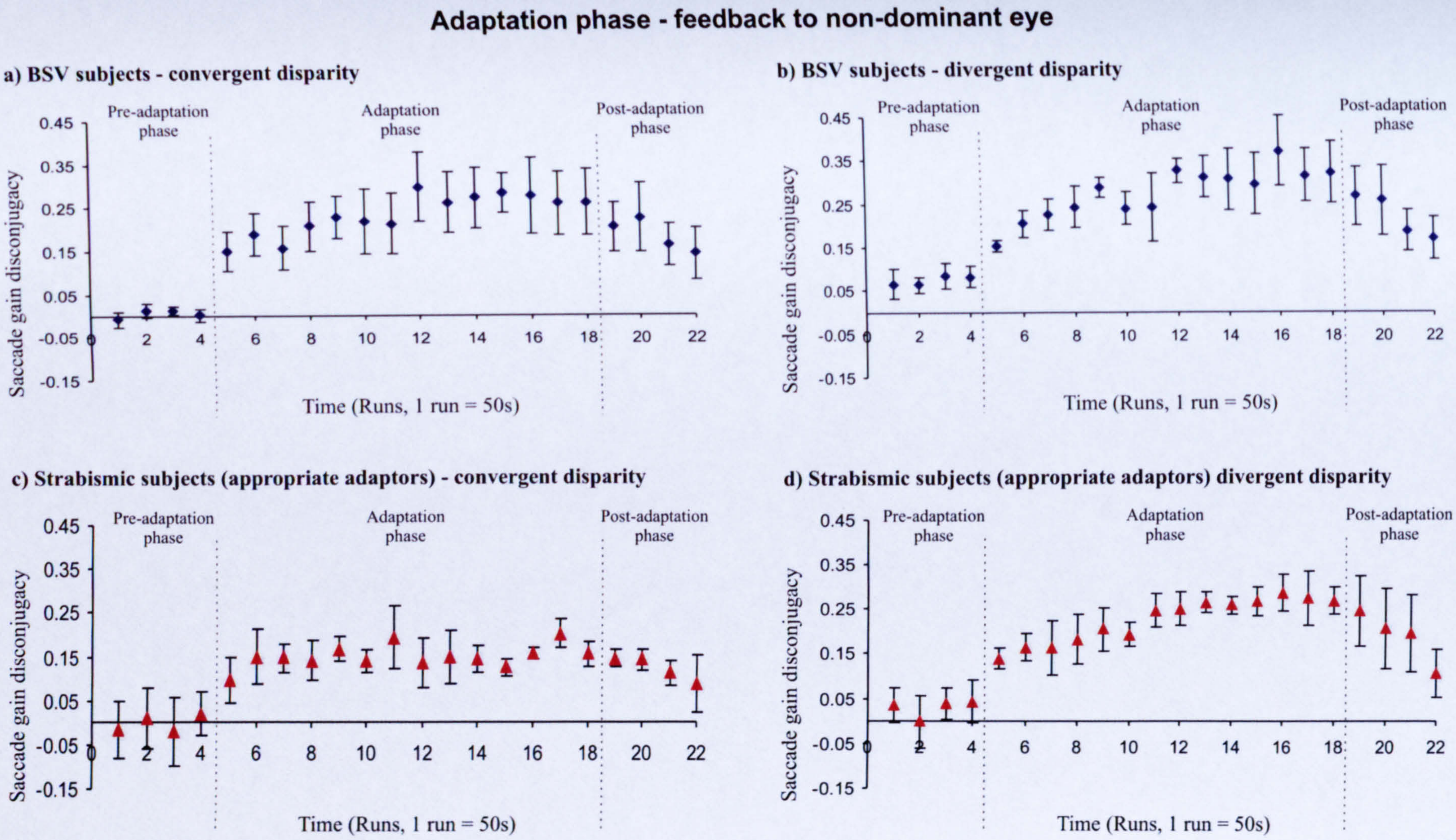


Figure 7.7: Mean saccade gain disconjugacy over the time course of the three experimental phases for BSV subjects (5, 6 & 8) and strabismic subjects (2, 4 & 6). Pooled data of three BSV subjects who received feedback to the non-dominant eye and three strabismic subjects who demonstrated appropriate disconjugate adaptation with feedback to the strabismic eye. Error bars represent +/- 1SE.

To test for differences in the rate of adaptation between groups two three-factor mixed measures ANOVA's were calculated, one for feedback to the dominant eye and one for feedback to the non-dominant eye. The three factors were group (BSV or strabismic), disparity (convergent or divergent) and time (run 5 to run 18). There was no significant difference between groups [dominant eye $F(1,4)=1.297$, $p>0.05$; non-dominant eye $F(1,4)=1.600$, $p>0.05$] or interactions between group and the other factors. The only significantly different factor was time, [dominant eye $F(13,52)=6.384$, $p<0.0001$; non-dominant eye $F(13,52)=6.778$, $p>0.0001$]. Details of the ANOVA are shown in Appendix 12.5.

The results show that both groups of subjects essentially have the same time course of adaptation, as demonstrated in Figures 7.6 and 7.7 and supported statistically.

7.5 Discussion

7.5.1 The no feedback condition

Hypothesis 1 stated that in subjects with BSV or strabismus with suppression there will be no difference in saccade disconjugacy at the end of an experimental test session compared to the beginning. This was tested by comparing the saccade gain disconjugacy, before and after the adaptation phase of 210 saccades, without feedback gain being applied. In both groups of subjects there was no difference in disconjugacy between the pre- and post-adaptation phases (Figures 7.3 and 7.5). The hypothesis is therefore supported.

The finding that subjects with strabismus with no clinically demonstrable binocular vision have stability in disconjugacy during such a task suggests that there is a degree of yoking of the eyes and that the two eyes are not operating independently.

7.5.2 The response to feedback gain in normal BSV

Hypothesis 2 stated that using an electronic feedback system in one eye to induce disparity, subjects with normal BSV will show an increase in saccade disconjugacy, which will persist when the feedback is ceased.

The electronic feedback system applied to a target visible to one eye produced rapid disconjugate saccade adaptation, which persisted when the feedback ceased, in all eight

subjects with normal bifoveal BSV. In contrast the control condition resulted in no significant difference in saccade disconjugacy between the pre- and post-adaptation phases. Hypothesis 2 was therefore supported.

This method of open-loop feedback has previously been described to induce symmetrical saccade adaptation (Albano & King, 1989) but this is the first description of its use monocularly with dissociation of the eyes, allowing the study of disconjugate adaptation. Figure 7.3 shows that the responses produced by the stimuli are large. This is because the eye under the feedback condition can never achieve the perfect saccade in response to the stimulus. As saccade amplitude is modulated in response to disparity the target continues to move further onwards.

7.5.3 The response to feedback gain in strabismus

Hypothesis 3 stated that using an electronic feedback system in one eye to induce disparity, subjects with strabismus and suppression will demonstrate saccade disconjugacy appropriate in direction for the stimulus. Anomalous responses reported by Bucci, Kapoula, Eggert and Garraud (1997) will not be found, as the angle of strabismus will not be corrected in the present study.

The primary aim of this study was to determine whether subjects with manifest strabismus and no demonstrable fusion, normal or anomalous, could produce disconjugate saccades under such test conditions. Figure 7.5 demonstrated that three of the six strabismic subjects studied were able to produce appropriate disconjugate adaptations despite no clinically detectable binocular co-operation. Two subjects (1 and 6) produced disconjugate adaptation inappropriate for the disparity and one subject had no response.

The electronic feedback system used to induce disparity in subjects with strabismus and suppression, demonstrated appropriate saccade disconjugacy in three subjects, therefore Hypothesis 3 is supported. Anomalous responses, similar to those reported by Kapoula, Eggert and Garraud (1997), were found in two of the subjects although the angle of strabismus was not corrected in the present study. Correction of the angle of strabismus does not therefore explain these previously reported responses; therefore this aspect of the Hypothesis is rejected.

7.5.3.1 Appropriate adaptation

The three subjects who adapted in the appropriate direction had small angled deviations (8Δ esotropia, 8Δ exotropia and 12Δ exotropia), who could be considered likely candidates for development of ARC and anomalous binocular vision. Extreme care was taken to clinically investigate the subjects with careful questioning for tests requiring subjective responses and a complete investigation was performed, employing a full range of tests; see results in Appendix 5. There was no clinical suggestion of any gross normal or abnormal binocular vision in any of the subjects. This finding has not been previously described in the literature.

Evidence for disconjugate adaptation in the strabismus with presence of gross clinically demonstrable binocular co-operation has been previously described. Using a different method (magnifying the image in one eye) Bucci Kapoula, Eggert and Garraud (1997) demonstrated disconjugate adaptations in intermediate sized strabismus with abnormal binocular vision. They describe such adaptations in two subjects with 18 and 21Δ esotropia who had positive responses for Bagolini striated glasses, failed to demonstrate stereoacuity in free space (TNO and Titmus test) but demonstrated a stereoacuity of 3600 seconds of arc on the synoptophore. The subjects reported in the present study however, differed as they had smaller angles of deviation and did not have demonstrable anomalous sensory fusion with Bagolini glasses or stereoacuity on the synoptophore.

7.5.3.2 Mechanisms for normal adaptation without fusion

The mechanism for the resulting difference in primary saccade amplitude in each eye in BSV is considered to be due to rescaling of the pulse step signal based on the post-saccadic disparity, with the primary aim of maintaining binocular single vision. Eggert, Kapoula and Bucci (1994) suggested another adaptive mechanism able to produce a saccade-initiated pre-programmed vergence command, this too would be disparity driven. A mechanism in the strabismic subjects who adapted normally or abnormally is less clear.

In the absence of fusion a benefit in maintaining the retinal image stimulating the deviating eye in a reasonably constant position might be to ensure that it remains within the suppression area, thus avoiding diplopia. If no adaptation or inappropriate adaptation occurred then the location of the image in the deviating eye would no longer stimulate retina equal to the angle of deviation, possibly causing symptoms. (None of

the subjects experienced diplopia or depth of the target during any of the conditions presented).

The pathway to drive such a response is unclear. It is possible that despite a lack of cortical perception of suppressed images that information from the strabismic eye is processed cortically or sub-cortically to allow adaptation of saccades and avoid diplopia.

The main body of evidence supports involvement of the cerebellum in adaptive control via cortical origins (Dichgans & Jung, 1974; Zee, Yee, Cogan, Robinson & Engel, 1976; Optican & Robinson, 1980). However, Hopp and Fuchs (2002) adapted two types of saccade generated through different neuronal pathways. These were targeting saccades, having long latencies and thought to involve higher cortical processing and express saccades, which have very short latencies thought to be processed sub-cortically (i.e. early visual areas, the SC and the brainstem, Fischer & Weber, 1993). Using an experimental gain-decreasing paradigm, gain was found to be adapted for both express and targeting saccades in similar proportions. This led to the conclusion that this rapid adaptation occurs after the pathways generating these two types of saccade converge, that is at or below the SC. A sub-cortical route programming saccade disconjugacy, without cortical processing and hence without the awareness of disparity, may therefore be possible.

7.5.3.3 Anomalous responses

Two of the six subjects demonstrated adaptation of saccades in a direction inappropriate (i.e. opposite) to the requirement for the induced disparity. This was consistently the case for subject 1 for all experimental sessions and both types of disparity, whereas subject 6 demonstrated normal adaptations, no response or inappropriate adaptive changes in different test sessions. Subject 1 had a small consecutive strabismus of just 2Δ exotropia and demonstrated the largest pre-adaptation phase disconjugacy of all subjects (mean 1.7°). Subject 6 had an 18Δ exotropia, the largest angle of strabismus studied in this experiment. These responses were not therefore related to size of strabismus.

Bucci, Kapoula, Eggert and Garraud (1997) have previously described anomalous adaptation responses in large angle esotropia ranging from 22 to 30Δ BO. These four subjects all had their angle of deviation corrected during the adaptation experiment, raising the question of whether such responses were due either to the subjects

attempting to revert to their original angle or being unable to make appropriate adaptations due to stimulation of retinal points not usually associated with each other. This current study suggests that this was not necessarily the case as inappropriate adaptation occurred in two subjects without prismatic correction of their angle. The results are also consistent with a study by Maxwell, Lemij and Collewijn (1995) of three subjects with constant strabismus, dense amblyopia and no binocular vision. These subjects wore a -3.00DS lens in front of the amblyopic eye for one week imposing a stimulus for making smaller saccades in the amblyopic eye. In all three the saccade size made by each eye changed after the one week adaptation period, in two subjects the saccades became smaller, however in one subject the saccades in the amblyopic eye became larger.

To investigate this response further it would be interesting to apply feedback in these subjects in the opposite direction. A feedback gain of -0.1 could be applied to the target of one eye. If saccade disconjugacy now reversed so that once more the disconjugacy was inappropriate for the induced disparity then this would be suggestive of a strategy of purpose.

7.5.3.4 Mechanisms for abnormal adaptation without fusion

Bucci, Kapoula, Eggert and Garraud (1997) proposed that the anomalous disconjugacy (inappropriate for induced disparity) seen in subjects with large angle strabismus and no fusion is driven by monocular visual input to improve fixation of each individual eye and not to reduce binocular disparity. They suggest that the disconjugate changes are driven by monocular visual input and movements of the two eyes are controlled independently, so-called utrocular vision (or vision with each eye separately) as described by Schor (1981). This is a primitive form of binocular vision found in vertebrates with complete decussation of the visual pathways. Bucci, Kapoula, Eggert and Garraud (1997) suggested that this form of independent eye control could allow avoidance of diplopia, but not establishment of a true binocular linkage. Why a change in disconjugacy during saccades under such test conditions would allow improved fixation of each eye is not clear. If fixation was improved by such disconjugacy then it might be anticipated that this would be the permanent angle of choice during all viewing conditions.

7.5.3.5 Clinical factors affecting adaptation

To determine if any specific characteristics regarding the diagnosis, history and treatment of the subjects, could explain why some subjects did, and others did not, show

adaptation, clinical details were considered in relation to the response to feedback. Table 7.10 summarises the main points of importance. These factors are discussed in this section.

The level of VA in the strabismic eye did not appear to prevent adaptation as the target was easily visible to the strabismic eye in all subjects and subject 9 adapted in the appropriate direction (although by a larger amount than the normal BSV group) despite having the lowest VA of the group (0.60 logMAR).

The age of onset of strabismus may have been an important factor as subjects 1 and 5 who demonstrated constant anomalous responses and no response respectively, reported an onset of strabismus before six months of age. This could not be verified, as medical records were not available for either of these subjects. On clinical examination they were the only two subjects to have asymmetrical monocular OKR with nasal to temporal response being reduced compared to the temporal to nasal response in subject 1 and absent in subject 5. This would appear therefore to support the early onset of strabismus in these cases (Mohn, Sireteanu & van Hof-van Duin, 1986; van Hof-van Duin & Mohn, 1986).

The maximum angle of deviation in which an appropriate adaptation response was found was 12Δ (one subject with 12Δ esotropia and one subject with 12Δ exotropia). The two subjects with strabismus measuring 18Δ, had no response and a variable mixed response. This finding is compatible with the results of Bucci, Kapoula, Eggert and Garraud (1997) who failed to find normal saccadic adaptation in four subjects with no demonstrable fusion and esotropia of between 14 and 30Δ. The difference in the two studies was that the subjects reported by Bucci, Kapoula, Eggert and Garraud (1997) were corrected with prisms to fully or partial correct the deviation, to present the disparities close to the fovea of the deviating eye. The subjects reported in this current study did not have the deviation corrected to determine how they would respond to such stimuli in their 'normal' sensory state. It appeared that the two subjects with angles of deviation >12Δ (both measuring18Δ) did not demonstrate normal saccade adaptation with their 'normal' strabismic angle. It would be interesting to repeat the experiment with larger angles of strabismus to determine whether this finding is consolidated.

a) normal adaptation

Subject	Diagnosis	Onset (years)	Surgery	PCT	Strabismic eye VA
2	constant ET with accom element	1	nil	8ΔET	-0.10
4	consecutive XT	3	Age 4 for esotropia, 2nd op weeks later as consecutive XT	12ΔXT	0.10
9	consecutive XT	1.5	Age 4 for ET	8ΔXT	0.60

b) mixed response – normal / anomalous adaptation

Subject	Diagnosis	Onset (years)	Surgery	PCT	Strabismic eye VA
6	Consecutive XT	2	Age 4 for ET, gradual XT 4/5 years later, now stable for at least 5 years	18XT	0.14

c) anomalous response

Subject	Diagnosis	Onset (years)	Surgery	PCT	Strabismic eye VA
1	Consecutive ET	? < 0.5	Age 53 for XT now stable for 6 years	2ΔET	0.20

d) no response

Subject	Diagnosis	Onset (years)	Surgery	PCT	Strabismic eye VA
5	Residual EOET	< 0.5	2 years for ET, gradual XT to 60Δ by age 34. Age 34 for consec. XT, now stable for 5 years	18ΔET	0.40

Table 7.10: Summary of clinical characteristics of subjects with each response to adaptation experiment. ET =esotropia, XT = exotropia, EOET = early onset esotropia, PCT = prism cover test, Δ = prism dioptre, VA = visual acuity (recorded as logMAR).

7.5.4 Time course of adaptation

In the binocular subjects adaptation occurred rapidly with the maximum increase occurring early in the adaptation phase within five to seven minutes. This was comparable with studies of conjugate (Deubel, Wolf & Hauske, 1986) and disconjugate adaptation (Kapoula, Eggert & Bucci, 1995). For divergent disparity the same time course and amount of adaptation occurred in the binocular subjects and three strabismic subjects who adapted normally. Similar amounts of adaptation occurred in both groups for convergent disparity, which were not statistically different, indicating that the strabismic subjects are capable of responding in the same way as BSV subjects.

The anomalous adaptation in subjects 1 and 6 had quite different patterns (shown in Appendix 12.2). In the adaptation phase subject 1 demonstrated an immediate large disconjugacy opposite to that required, occurring within the first fifteen saccades. This was very variable throughout the adaptation phase and did not show the gradual increase seen in normal adaptation. Subject 6, for convergent disparity, made appropriate direction saccade disconjugacy for the first three runs of recording (45 saccades). In the fourth run an abrupt change is seen where disconjugacy changes to an inappropriate direction and remains at a similar but variable amount. These patterns are perhaps more suggestive of a deliberate strategy to deal with the stimulus rather than an adaptive process.

7.6 Conclusion

An electronic open-loop feedback system, applied to one eye under conditions of dissociation, induced large saccade disconjugacy in normal BSV. Binocular vision is not required for disconjugate saccade adaptation. Five of the six subjects with strabismus demonstrated disconjugate changes. Three subjects with manifest strabismus, no potential normal BSV or clinically demonstrable anomalous BSV and angles of deviation up to 12Δ, (one esotropia and two exotropia), demonstrated normal control of binocular saccades in response to induced disparity. They demonstrated a rapid disconjugate adaptation of saccades in an appropriate direction of similar size and time scale to subjects with normal BSV. Two subjects (one esotropia and one exotropia) demonstrated adaptations 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 six months did not demonstrate normal adaptation.

Both peripheral (Experiment 5) and central targets (Experiment 9) presented within the suppression area of subjects with constant strabismus have been shown to affect saccadic programming.

Chapter 8

Final summary and discussion

The mechanism of suppression in strabismus is unclear and contribution of the suppressing eye to visual function has received little attention in the literature. This thesis investigated how the strabismic eye contributes to saccade generation in the presence of strabismus with suppression and also considered the effect of the strabismic eye in the presence of ARC.

8.1 Experimental equipment

Due to the lack of a suitable commercially available system for presenting projected targets to one or both eyes a system was designed and built for the purpose of this thesis. Four liquid crystal shutters were used which provided high light transmission, rapid opening and silent operation. Experiments 2 and 7 tested the reliability of this system in subjects with normal visual function and subjects with strabismus and suppression respectively. When the shutter in front of the projector was closed the targets were invisible on the screen. This was confirmed using a forced choice procedure where subjects with normal visual acuity were unable to detect the target (Experiment 2, Chapter 3). In strabismic subjects, two targets were presented on the screen, one visible to each eye. The target presented to the strabismic eye was not detected, indicating that the method of dissociation did not break down suppression (Experiment 7, Chapter 6). This method therefore, provides a useful tool for future studies of eye movements in binocular vision and strabismus.

A mirror galvanometer was used to move projected targets on the back projection screen as saccadic stimuli. During pilot experiments the author was aware, under careful observation, that for large target eccentricities as the targets moved they appeared to sweep across the screen. Experiment 1, Chapter 3 was designed to test whether the mirror galvanometer was a suitable method for producing saccadic stimuli. A mask, which eliminated any appearance of the target on the screen as it moved between target locations, was used to test this. Saccade characteristics with and without masking of the screen were not significantly different and therefore the method was considered appropriate.

8.2 Binocular and monocular distractors in BSV

The experiments of Chapters 5 and 6 were motivated by the study of Walker, Deubel, Schneider and Findlay (1997). The first objective of Chapter 5 was to repeat their study with the laboratory set-up described in Chapter 2. This was successful in that comparable results for saccade latency and accuracy were obtained with distractors presented to both eyes. The reciprocal effect of latency and accuracy described by Walker, Deubel, Schneider and Findlay (1997) was replicated, with latency affected for contralateral distractors to the target and accuracy affected for distractors ipsilateral to the target. In both studies the maximum effect on saccade latency was found to be with distractors presented at the original fixation point.

This work was explored further to determine whether, in subjects with normal BSV, monocular distractors had an equal effect to binocular distractors. Also to determine whether distractors presented to the dominant eye had greater effect than distractors presented to the non-dominant eye.

The findings were that distractors presented to the dominant eye or non-dominant eye had equal effect on both saccade latency and accuracy. It was concluded therefore that each eye has equal input into saccade generation. Binocular distractors were found to cause a greater difference in latency, for contralateral distractors compared to ipsilateral distractors, than monocular distractor presentations. The effect of binocular distractors on saccade gain was also significantly larger than monocular distractor presentations. Therefore in BSV the summated sensory signal has a greater effect on the motor response. These results were used for comparison to those of subjects with strabismus.

8.3 Distractors in strabismus

Monocular distractors presented to the fixing eye or the strabismic eye in six subjects with strabismus and suppression produced different results. Distractors presented within the suppression area of the strabismic eye did have an effect on saccade latency and accuracy, however this effect was small compared to a large response to distractors presented to the fixing eye. The effect on latency was approximately a quarter of that found in the non-dominant eye in normal BSV and the effect on accuracy was approximately a third of the size. A significant finding with distractors presented to the strabismic eye was that the maximum increase in saccade latency, typically found in normal BSV to occur with distractors at the original fixation point, occurred at a point stimulating the area of the anatomical fovea of the deviating eye.

There was no difference in the effect on latency with distractors presented monocularly to the dominant fixing eye and the response found with binocular distractors. Suppression of images of one eye results in lack of sensory summation of inputs in the striate cortex and is therefore consistent with this finding. However in three subjects a larger effect on saccade accuracy did occur with binocular distractors compared to monocular distractors to the fixing eye.

It has previously been suggested that in strabismus saccades are generated based on visual input from the dominant (fixing) eye only (van Leeuwen, de Faber, van der Steen & Collewijn, 1995). This conclusion was reached, as the accuracy of saccades in the dominant eye of ten subjects with constant strabismus was comparable to binocular subjects (van Leeuwen, de Faber, van der Steen & Collewijn, 1995). The accuracy of saccades was unchanged by covering the strabismic eye, whilst covering the dominant eye resulted in decreased accuracy independent of visual acuity. In this thesis, whilst information from the dominant eye had most effect on saccade generation, information from the strabismic eye (with suppression) also affected latency and accuracy of saccades.

Experiment 6, Chapter 6 confirmed that distractors presented to the strabismic eye of subjects with suppression were not detected by any of the subjects. This therefore raises questions regarding the mechanism for an effect of distractors on motor performance despite lack of sensory perception of the images. The site of suppression is unknown however, as discussed in Section 1.4.6.2 most evidence suggests that it occurs within the striate cortex. The findings therefore may suggest that information from the suppressed eye is available to the saccadic system by a sub-cortical pathway, directly from the retina to the superior colliculus (retino-collicular pathway outlined in Section 1.2.1.2). An alternative possibility is for a high sensitivity in suppression for detection of transient onset and offset of a target such that briefly presented targets are perceived cortically but the subject fails to consciously register them.

Experiment 8, Chapter 6 considered the effect of monocular and binocular distractors in two subjects with strabismus and ARC. Both subjects had constant small angled strabismus with demonstrable sensory and motor fusion and gross stereoacuity on clinical testing. The effect on saccade latency from distractors in the strabismic eye was just under half of the effect found in the non-dominant eye of subjects with normal BSV. The effect on gain was equal with distractors in the strabismic eye and in the fixing eye and similar to the effect in the BSV subjects. An interesting finding was that the distractor position giving rise to the largest increase of saccade latency was the original fixation point, and not the position stimulating the fovea as was found in the suppressing subjects.

The increase in saccade latency with distractors at the original fixation point has been explained as an increase in activity of the fixation cells in the rostral pole of the superior colliculus (see Section 1.2.3.1) (Doris & Munoz 1995, Munoz & Wurtz 1992, 1993a, b, 1995 a, b). These fixation cells show a tonic discharge during fixation and represent the central 2° of the visual field. Stimulation of these 'fixation cells' has an inhibitory effect on saccades (Munoz & Wurtz, 1993b). In strabismic subjects with suppression the maximum increase occurred when distractors were at an eccentricity equal to the fovea and not when distractors appeared at the location of original fixation. Hence it is possible that the fixation cells were responding in relation to the foveal activity of the strabismic eye. In contrast, where anomalous BSV existed, the maximum increase in latency occurred with distractors at the original fixation point, i.e. stimulation of the pseudo-fovea and not in relation to the anatomical fovea. Fixation cells in this situation were possibly responding to stimulation of an area other than the anatomical fovea, which may represent a collicular re-mapping in the presence of ARC. Further work in this area would be required to confirm this.

8.4 Disconjugate saccade adaptation in BSV

In contrast to the distractor experiments, which considered saccade generation in relation to peripheral distractors or non-targets, Experiment 9, Chapter 7 explored the role of the central fixation target in saccade generation. The stimulus consisted of two identical overlapping targets, one visible to each eye. Electronic feedback could be applied to one target so that as the eye moved, the target also moved in the same direction. This provided a stimulus to induce saccade disconjugacy.

In eight subjects with normal BSV, rapid disconjugate saccade adaptation occurred to partially correct the induced disparity. Although there were differences in the time course of adaptation between subjects, the majority demonstrated a rapid increase in disconjugacy over a period of 5 minutes, which then levelled off. There was no significant difference in the rate of adaptation for convergent or divergent disparities.

8.5 Disconjugate saccade adaptation in strabismus

The disconjugate adaptive control of gain using the electronic feedback open loop paradigm proved a successful way to investigate the input of the suppressing eye in strabismus to saccade generation. In Experiment 9, five out of six subjects with constant strabismus and suppression demonstrated disconjugate saccade adaptation. Three of these subjects produced disconjugacy appropriate for the disparity whilst in two subjects the disconjugacy was in an inappropriate direction. The time course of adaptation in the

three subjects who responded appropriately was not significantly different from the BSV subjects, suggesting that the same mechanism is involved in both groups.

The results raise the questions of how and why the strabismic eye adapts in this way. The purpose of such a response may be a diplopia avoidance strategy such that the retinal image stimulating the deviating eye is maintained in a reasonably constant position, ensuring that it remains within the suppression area.

The pathway to drive such a response is unclear. It is possible, despite a lack of cortical perception of suppressed images that information from the strabismic eye is used at a sub-cortical level to allow adaptation of saccades and avoid diplopia. Hopp and Fuchs (2002) concluded that this type of rapid saccade adaptation occurs at or below the superior colliculus. A sub-cortical pathway for programming saccade disconjugacy, without cortical processing and hence without the awareness of disparity, may therefore be possible.

A non-geniculostriate input to the extrastriate cortex (motion-sensitive area V5) has been identified in humans (Holliday, Anderson & Harding, 1997). It is proposed that this pathway mediates the residual visual functioning found in blindsight. This may therefore indicate that motor changes to saccades with the absence of visual perception found in this current study are cortically mediated but via a route that bypasses striate cortex. It is possible that it is striate cortex, where suppression might be occurring in strabismic subjects, that determines awareness of visual stimuli whilst an extrastriate cortical route allows visual information to be used for saccade programming.

The responses demonstrated from the strabismic eye in both the distractor and adaptation experiments may represent a primitive response allowing reaction to information of a threat or approaching danger perceived from that eye.

8.6 Clinical significance

The overall findings of this thesis may give some insight as to why some patients with constant suppression of one eye and no demonstrable binocular vision incur post-operative problems of disorientation following correction of strabismus.

Maintaining the maximum level of visual acuity, by refractive correction of the strabismic suppressing eye, may be of continued benefit throughout adulthood to give the optimum chance of using information from the suppressing strabismic eye.

The clinical significance of these findings may be that stabilisation of angle of strabismus is more likely in patients who use information from the suppressing eye in

this way. Although clinical tests may reveal no demonstrable binocular co-operation of the eyes, it is possible that the eyes are behaving as a yoked pair. This may therefore lead to a better prognosis for stability in the angle than predicted clinically. Follow-up of the strabismic subjects studied in this thesis would be required to substantiate this.

8.7 Further research

Experiment 9 concluded that three out of six subjects with strabismus and suppression were able to make appropriate disconjugate saccades in response to disparity, whilst two made adaptations in an inappropriate direction and one had no change in disconjugacy to the stimulus. Further research to examine the post-saccadic period would possibly establish the differences in these subjects. It is possible that subjects who were more able to produce appropriate vergence movements were those who altered the size of the primary saccade, whereas those who could not verge would not benefit from attempting to produce disconjugate saccades.

As previously suggested (Experiment 9) to further investigate the response of inappropriate adaptation it would be interesting to apply feedback to the same subjects in the opposite direction. If saccade disconjugacy reversed then this would be suggestive of a consistent strategy.

The strabismic observers in this present study all had relatively small angles of deviation (<18Δ). It would therefore be of further interest to extend the current experiments to include observers with suppression and larger angles of deviation to determine whether there is an upper limit for contribution of the strabismic eye to saccade programming. It may be that the effect diminishes as the angle increases due to either anatomical differences of peripheral retina or the fovea becoming too remote from the target to influence the saccade.

Occasionally patients with longstanding constant strabismus, suppression and no demonstrable BSV, who have recently undergone corrective surgery, notice instability and general lack of co-ordination post-operatively. Could this be the group of subjects who have binocular co-operation despite no clinical evidence for this? If we consider a patient with 30Δ esotropia, objects within the periphery (approximately 15° from central fixation) stimulating the fovea of the deviating eye would have maximum influence over saccade generation. If surgically this were reduced to <10Δ, it would then be objects within 5° of the central fixation target that would have maximum influence on saccade generation, which may have a much greater effect on co-ordination and fixation of the central target. Distractor and adaptation experiments performed pre and post-operatively may reveal why such problems are encountered.

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Appendix 1

Ethics approval

Ethics Office location: 307 Western Bank, Royal Hallamshire Hospital, Glossop Road, Sheffield S10 2JF
Tel & Fax No *Enquiries (0114) 271 2394/New Registrations 271 1789*
E-mail: External: Kate.Khoazi@sth.nhs.uk

Chairman: Professor C J Taylor/ Administrator: Ms K A Khoaz

SSREC

SOUTH SHEFFIELD RESEARCH ETHICS COMMITTEE

Always quote the relevant SSREC Registration Number

CJT/SM 15/11/2001

Miss. H Griffiths, Lecturer
Ophthalmology & Orthoptics
O Floor, RHH

Dear Miss.Griffiths

Ref.: SS/01/232 - Eye movement control in subjects with strabismus

The above study was seen on 1/11/2001 and I can now confirm unreserved Ethics Committee approval subject to the following terms and conditions:

1. That you familiarise yourself with the ICH Guidelines laid down for the conduct of human experiments.
2. It is understood that approval of the investigation does not absolve you from total responsibility for the safety and well being of the subjects.
3. No deviations from or changes of the protocol will be initiated without prior written approval of an appropriate amendment, (*except when necessary to eliminate immediate hazards to the subjects or when the change(s) involve only logistical or administrative aspects of the trial).* Amendments should be reported in a standardised format giving indication of the local implications as well as a brief outline of what the amendment(s) consist of (outline attached) and its significance or otherwise in terms of the overall protocol.
4. That you should promptly report any changes increasing the risk to subjects; or new information that may affect adversely the safety of the subjects or conduct of the trial. All Unexpected Serious adverse drug reactions (SADR's) should be reported in a standardised format (outline attached) within 7-15 days as specified in the EU Directive. These should be submitted with relevant interpretation from the investigator and sponsor on the significance for the conduct of the trial. *(an acknowledgement and/or opinion as to whether approval will continue will be sent within a few days following review by the Ethics Committee)*
5. That should any untoward event occur during the conduct of the study the Chairman of the Committee or failing this, the Administrator be informed immediately. Reports of progress shall be submitted at yearly intervals.

The documents approved were:

Protocol version 1 : Dated September 2001	✓
Information sheet for control group : Date received 15/11/01	✓
Information sheet for strabismic group ; Date received 15/11/01	✓
Consent form version 1 : Date received 14/9/01	✓

I can confirm that this Ethics Committee is organised and operates according to GCP and the applicable laws and regulations

Yours sincerely

Professor C Taylor
Chairman

C:\EthShared\!admin-team\Sam\Final Approval\Griffiths -01-232-15-11-01.doc

Appendix 2

Consent form

Centre Number: RHH
Study Number: SS/01/232
Patient Identification Number for this trial: S8

Title of Project: Eye Movement Control in Strabismus

Name of Researcher: Helen Griffiths

Please initial box

1. I confirm that I have read and understand the information sheet dated 14.9.01 for the above study and have had the opportunity to ask questions. ☐

2. I understand that my participation is voluntary and that I am free to withdraw at any time, `without giving any reason, without my medical care or legal rights being affected. ☐

3. I understand that sections of any of my medical notes may be looked at by responsible individuals from University of Sheffield where it is relevant to my taking part in research. I give permission for these individuals to have access to my records. ☐

4. I agree to take part in the above study. ☐

Name of Patient	Date	Signature
Name of Person taking consent (if different from researcher)	Date	Signature
Researcher	Date	Signature

Copies: 1 for patient; 1 for researcher; 1 to be kept with hospital notes

Appendix 3

Statistical analysis for Chapter 3

Experiment 1

A3.1 Saccade latency with and without masking of the screen

3 factor repeated measures analysis of variance

Factors

1. Screen	masked / unmasked	m
2. Saccade	right / left	s
3. Saccade amplitude	5° / 10° / 15°	p

	DF	SS	MS	F	P	epsilon
Subjects	3	7633.790	2544.597			
m	1	13.104	13.104	0.092	0.7815	
Error	3	427.477	142.492			1.00
s	1	178.255	178.255	5.281	0.1052	
Error	3	101.258	33.753			1.00
ms	1	0.040	0.040	0.001	0.9751	
Error	3	104.055	34.685			1.00
p	2	1022.818	511.409	3.399	0.1031	
Error	6	902.855	150.476			0.63
mp	2	14.661	7.331	0.7467	0.307	
Error	6	143.347	23.891			0.57
sp	2	35.789	17.895	0.136	0.8756	
Error	6	790.537	131.756			0.50
msp	2	20.824	10.412	0.496	0.6318	
Error	6	125.918	20.986			0.94

A3.2 Saccade gain with and without masking of the screen

3 factor repeated measures analysis of variance

Factors

1. Screen	masked / unmasked	m
2. Saccade	right / left	s
3. Saccade amplitude	5° / 10° / 15°	p

	DF	SS	MS	F	P	epsilon
Subjects	3	0.026	0.009			
m	1	0.007	0.007	3.068	0.1781	
Error	3	0.006	0.002			1.00
s	1	0.003	0.003	0.268	0.6404	
Error	3	0.034	0.011			1.00
ms	1	0.001	0.001	0.854	0.4235	
Error	3	0.005	0.002			1.00
p	2	0.187	0.093	41.880	0.0003	
Error	6	0.013	0.002			0.52
mp	2	0.004	0.002	2.126	0.2005	
Error	6	0.006	0.001			0.60
sp	2	0.006	0.003	3.143	0.1165	
Error	6	0.006	0.001			0.72
msp	2	0.001	0.000	0.413	0.6794	
Error	6	0.006	0.001			0.96

A3.3 Saccade peak velocity with and without masking of the screen

3 factor repeated measures analysis of variance

Factors

1. Screen	masked / unmasked	m
2. Saccade	right / left	s
3. Saccade amplitude	5° / 10° / 15°	p

	DF	SS	MS	F	P	epsilon
Subjects	3	16685.641	5561.880			
m	1	4715.376	4715.376	4.142	0.1347	
Error	3	3415.108	1138.369			1.00
s	1	2500.864	2500.864	1.219	0.3502	
Error	3	6155.171	2051.724			1.00
ms	1	299.151	299.151	0.572	0.5043	
Error	3	1567.959	522.653			1.00
p	2	201684.658	100842.329	104.892	0.0000	
Error	6	5768.360	961.393			0.98
mp	2	1389.305	694.652	2.719	0.1443	
Error	6	1532.660	255.443			0.70
sp	2	69.953	34.976	0.043	0.9580	
Error	6	4860.357	810.059			0.61
msp	2	837.606	418.803	2.778	0.1400	
Error	6	904.700	150.783			0.59

Experiment 2

A3.4 To test for a difference in the number of correct responses with use of the metal and LCP shutter.

Paired t-tests

Hypothesised difference = 0

metal / lcp shutter – R & L responses

Mean diff.	DF	t-value	p-value
-4.640	4	-0.992	0.3774

metal / lcp shutter – R responses

Mean diff.	DF	t-value	p-value
-8.140	4	-0.757	0.4911

metal / lcp shutter – L responses

Mean diff.	DF	t-value	p-value
-1.440	4	-0.210	0.8438

Appendix 4

Shutter control for Chapter 3, Experiment 2

Target preset	Presentation Number																			
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
1	L	L	R	L	L	L	R	R	L	L	R	L	R	R	R	R	R	R	L	R
2	R	L	L	R	L	L	L	R	L	L	L	R	R	L	R	R	R	L	R	R
3	R	R	R	L	R	L	R	R	L	L	L	R	L	R	L	L	R	R	R	L
4	R	L	L	L	L	R	L	R	R	R	R	R	L	L	L	L	R	L	R	R

Shutter sequence	Presentation Number																			
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
1	O	LC	LC	O	LC	LC	LC	LC	O	LC	LC	LC	LO	LC	LC	LC	LC	LC	LO	LC
2	MC	O	O	MC	MC	MC	O	MC	O	O	MC	O	MC	MC	O	MC	O	O	MC	O
3	MC	LC	LC	MC	MC	MC	LC	MC	O	LC	MC	LC	MC	MC	LC	MC	LC	LC	MC	LC

L = Target to left
R = Target to right
O = all shutters open
MC = metal shutter closed
LC = LCP shutter closed

Total of 8 runs using the following target presets:
Target preset: 1, 2, 3, 4, -1, -2, -3, -4 in random order

Total presentations = 160 of which:

All shutters open	=	24
LCP shutters closed	=	96
Metal shutters closed	=	40

Appendix 5

Strabismic subjects clinical details

Subject: 1 **DOB:** 23.12.1940

Date: 29.7.02

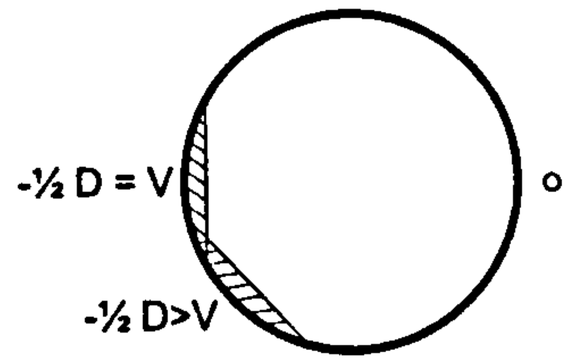
History: Left exotropia onset approx 6 months of age. Glasses for hypermetropia prescribed in childhood. Surgery for exotropia at 56 years of age. LLR rec^{n}, LMR resect^{n}, RLR rec^{n}. Right occlusion treatment for left amblyopia.

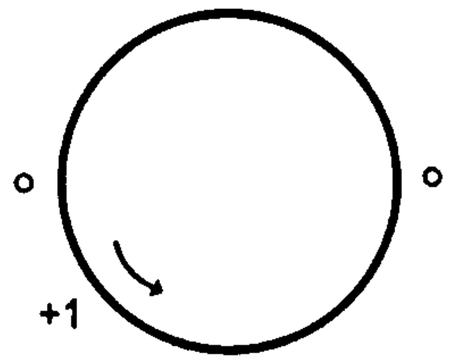
Refractive Error: RE +2.25, LE +3.00/-0.50 x 180

Visual Acuity: with glasses RE 6/5 LE 6/12 SN
-0.10 0.20 logMAR

Cover Test:
1/3m & 6m very slight left exotropia

Ocular Movements:



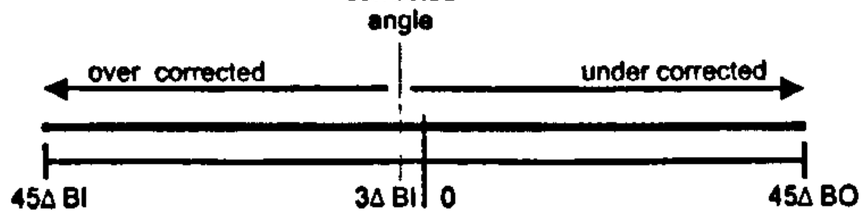


Convergence: With reducing angle to 12cm then LE diverges without diplopia

Binocular Function: (with glasses)

Worth's Lights	**N & D** left suppression
Bagolini	**N & D** left suppression
Pol. 4 dot	**1/3m to 6m** left suppression
Stereo	**TNO/Frisby/Lang** negative
Fusion Range:	**N & D** nil

Suppression: **Area:**



Density: filter 15

•••• = diplopia
—— = suppression

PCT 1/3m: 2Δ XT **1.14m** 2Δ XT
6m: 3Δ XT

Synoptophore: **Obj. Angle** +1° **Subj. Angle** not possible
Fusion: nil demonstrable with peripheral slides

OKR: **N-T** = reduced **T-N** = normal

Subject: 2 **DOB:** 31.7.79

Date: 24.4.02

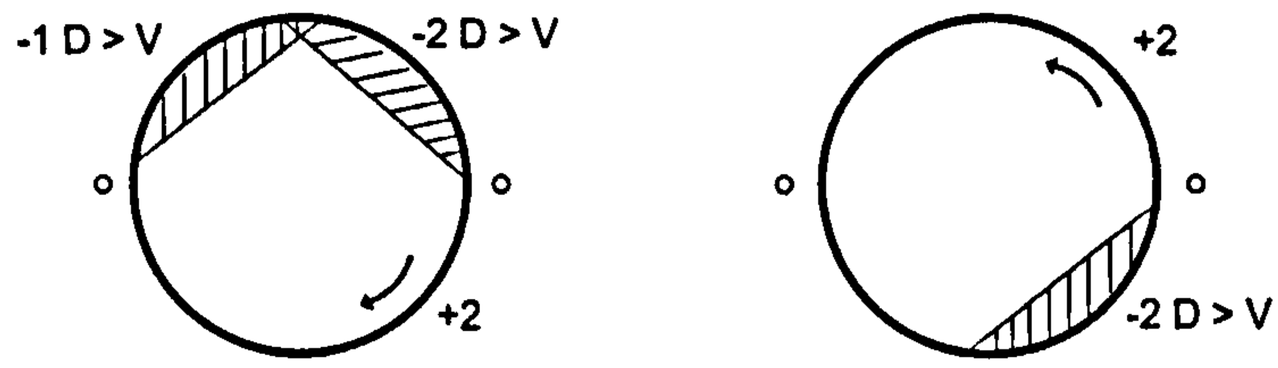
History: Right esotropia noticed by parents from 1 year of age. Glasses for hypermetropia prescribed at 3 years of age. Left occlusion treatment for right amblyopia from 3 years of age.

Refractive Error: RE +6.50/-0.25 x 90, LE +5.50

Visual Acuity: with CL's RE 6/6 LE 6/5 SN
6/6 6/6 red SN
0.00 -0.10 logMAR

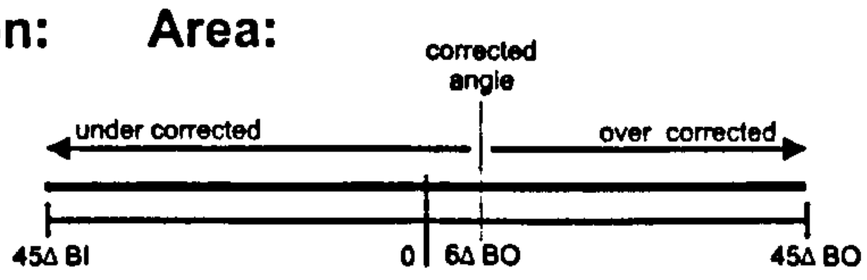
Cover Test: with CL's
1/3m & 6m slight right esotropia with very slight right hypotropia

Ocular Movements:



Binocular Function: (with CL's)
Worth's Lights **N & D** right suppression
Bagolini **N & D** right suppression
Pol. 4 dot **1/3m to 6m** right/alternating suppression
Stereo **TNO/Frisby/Lang** negative
Fusion Range: **N & D** nil

Suppression: **Area:**



Density: filter 8

•••• = diplopia
— = suppression

PCT 1/3m: 10Δ ET 3Δ RHoT **1.14m** 6Δ ET 3Δ RHoT
6m: 6Δ ET 3Δ RHoT

Synoptophore: **Obj. Angle** +4° 4ΔL/R **Subj. Angle** not possible
Fusion: nil demonstrable with peripheral slides

Fixation: **Right** Central **Left** Central

OKR: **N-T** = normal **T-N** = normal

Subject: 3 **DOB:** 9.1.82

Date: 8.3.02

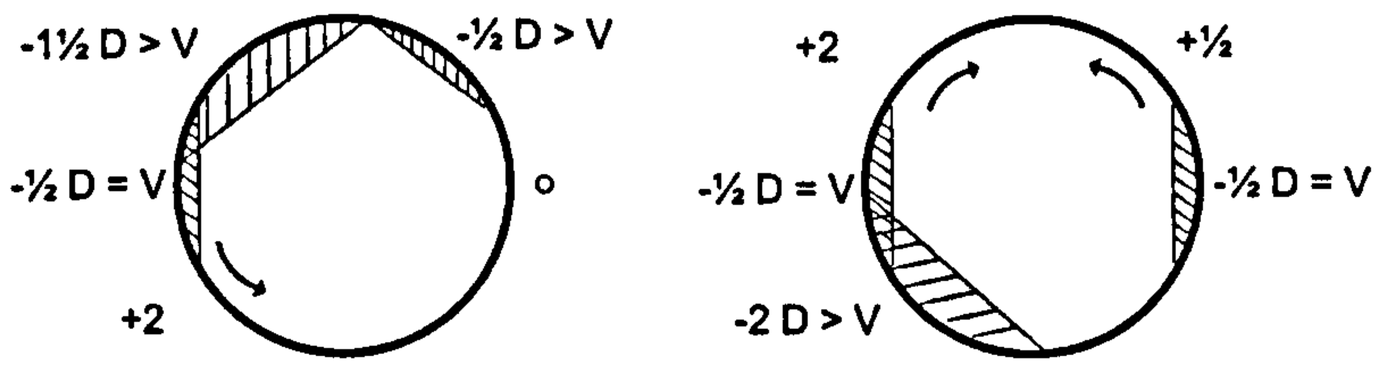
History: Right esotropia noticed by parents from 6 months of age.
Glasses for hypermetropia prescribed at age 9 months.
Surgery for esotropia at 13 months and 16 months of age.
Left occlusion treatment from age 1 to 6 years.

Refractive Error: RE +3.00/-0.50 x 4, LE +3.25/-0.75 x 174

Visual Acuity: with glasses RE 6/5 LE 6/4 SN
6/6 6/6 red SN
-0.10 -0.14 logMAR

Cover Test:
1/3m & 6m slight right esotropia with very slight right hypotropia and DVD

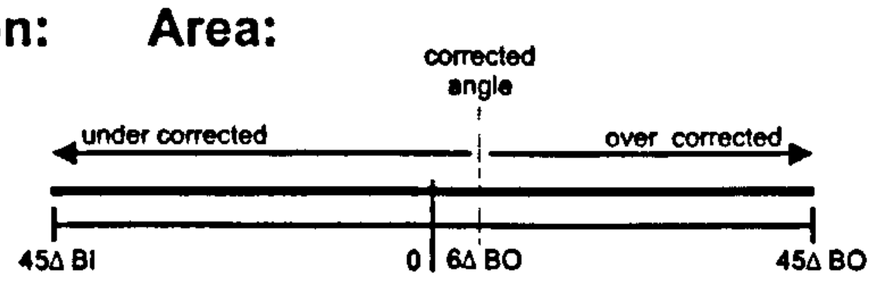
Ocular Movements:



Convergence: With decreasing angle to 15cm then EE diverges without diplopia

Binocular Function: (with glasses)
Worth's Lights **N & D** right/alternating suppression
Bagolini **N & D** right suppression
Pol. 4 dot **1/3m to 6m** right suppression
Stereo **TNO/Frisby/Lang** negative
Fusion Range: **N & D** nil

Suppression: **Area:**



Density: filter 10

•••• = diplopia
— = suppression

PCT 1/3m: 6Δ ET 2Δ RHoT **1.14m** 6Δ ET 2Δ RHoT
6m: 6Δ ET 2Δ RHoT

Synoptophore: **Obj. Angle** +3° 2ΔL/R **Subj. Angle** +3° 1ΔL/R
Fusion: nil demonstrable with peripheral slides

Fixation: **Right** Central **Left** Central

OKR: **N-T** = reduced **T-N** = normal

Subject: 4 **DOB:** 31.7.61

Date: 22.7.02

History: Parents noticed squint at approx age 3. Surgery at age 3 led to over correction therefore 2nd operation soon after. No glasses, right occlusion from age 3-5 years. No signs or symptoms noticed at time of testing.

Refractive Error: RE +0.75, LE +0.50/+0.25 x 170 - no glasses

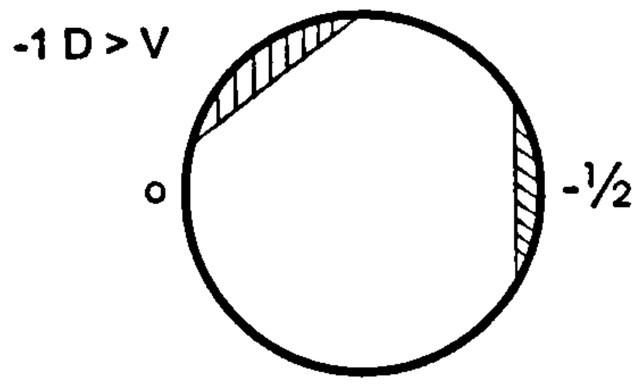
Visual Acuity:

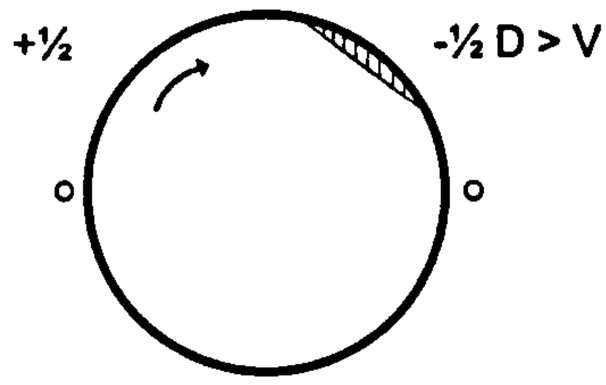
RE 6/4	LE 6/6 SN
6/6	6/9 red SN
-0.10	0.00 logMAR

Cover Test:

1/3m slight left exotropia
6m slight+ left exotropia

Ocular Movements:



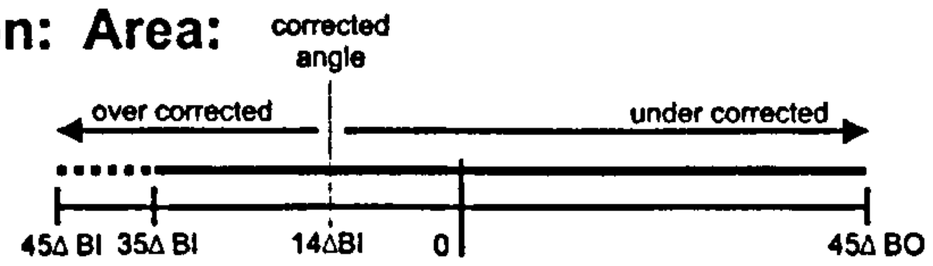


Convergence: With decreasing angle to 8cm then LE diverges without diplopia

Binocular Function:

Worth's Lights	**N & D** left suppression
Bagolini	**N & D** left suppression
Pol. 4 dot	**1/3m to 6m** left suppression
Stereo	**TNO/Frisby/Lang** negative
Fusion Range:	**N & D** nil

Suppression: Area:



Density: filter 6

•••• = diplopia
— = suppression

PCT 1/3m: 10Δ XT **1.14m** 12Δ XT
6m: 14Δ XT

Synoptophore: **Obj. Angle** -5° **Subj. Angle** -5°
Fusion: nil demonstrable with peripheral slides

Fixation: **Right** Central **Left** Central

OKR: **N-T** = normal **T-N** = normal

Subject: 5 **DOB:** 25.1.63

Date: 31.7.02

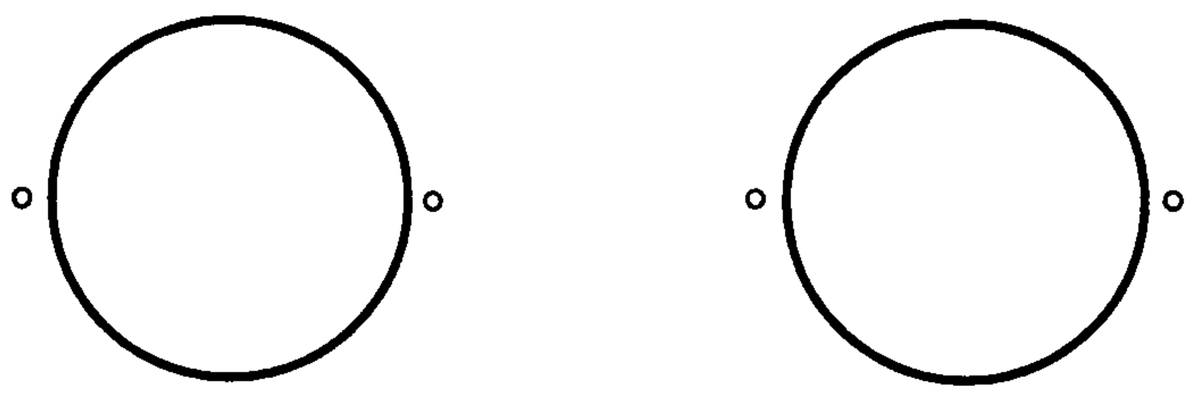
History: Esotropia from birth. No glasses. Left occlusion for right amblyopia with limited success. Surgery for esotropia at age 2 years. Gradual consecutive exotropia. Surgery for exotropia in 1997, RLR rec", RMR resect".

Refractive Error: nil

Visual Acuity: RE 6/24 LE 6/5 SN
6/24 6/6 red SN
0.40 -0.10 logMAR

Cover Test:
1/3m & 6m slight right esotropia

Ocular Movements:

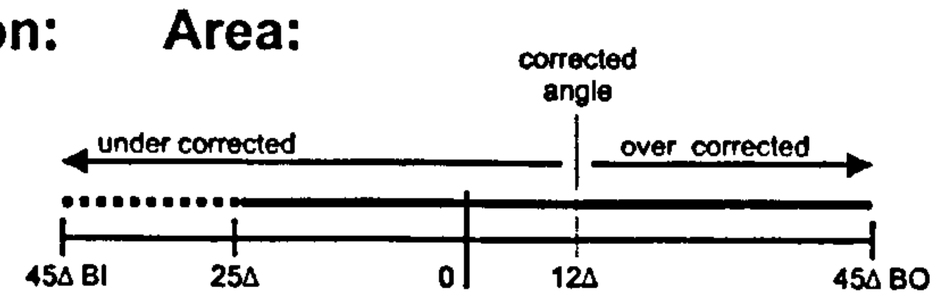


Convergence: With angle to 6cm without diplopia

Binocular Function:

Worth's Lights	**N & D** right suppression
Bagolini	**N & D** right suppression
Pol. 4 dot	**1/3m to 6m** right suppression
Stereo	**TNO/Frisby/Lang** negative
Fusion Range:	**N & D** nil

Suppression: **Area:**



Density: filter 14

···· = diplopia
— = suppression

PCT 1/3m: 12Δ ET **1.14m** 12Δ ET
6m: 12Δ ET

Synoptophore: **Obj. Angle** +7° **Subj. Angle** no possible
Fusion: nil demonstrable with peripheral slides

Fixation: **Right** parafoveal nasal **Left** Central

OKR: **N-T** = absent **T-N** = normal

Subject: 6 **DOB:** 20.6.80

Date: 19.6.00

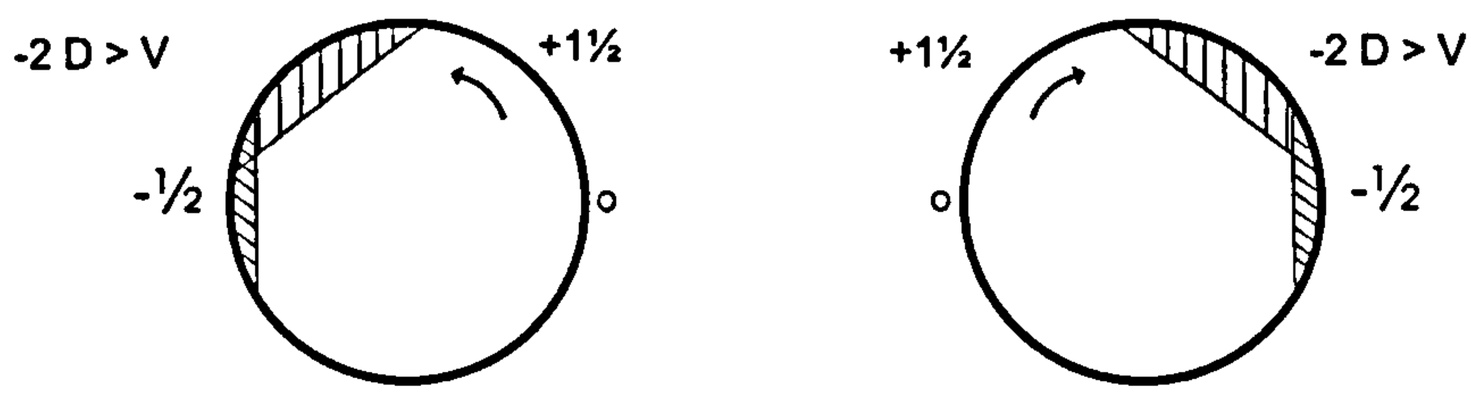
History: Esotropia noticed from approx 6 months of age but nil detected at hospital eye test until approx 18 months of age. Squint operation at age 4 for esotropia. Right occlusion until approx age 7.

Refractive Error: RE +4.00, LE +6.00

Visual Acuity: RE 6/5 LE 6/6 SN
6/6 6/6 red SN
-0.10 0.00 logMAR

Cover Test:
with glasses 1/3m slight/mod left exotropia with v sl left hypertropia
6m slight+ left exotropia
w/o glasses 1/3m & 6m v sl left esotropia with v sl left hypertropia

Ocular Movements:

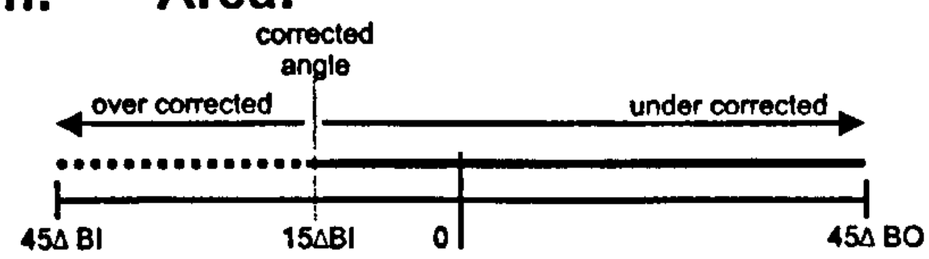


Convergence: With decreasing angle to 12cm then LE diverges without diplopia

Binocular Function:

Worth's Lights	**with glasses N & D** left suppression
Bagolini	**with glasses N & D** left suppression
Pol. 4 dot	**1/3m to 6m** left suppression
Stereo	**TNO/Frisby/Lang** negative
Fusion Range:	**N & D** nil

Suppression: **Area:**



Density: filter 5

···· = diplopia
— = suppression

PCT 1/3m: 20Δ XT 5Δ LHT **1.14m** 15Δ XT 2Δ LHT
6m: 15Δ XT

Synoptophore: **Obj. Angle** -9° 2Δ L/R **Subj. Angle** left suppression
Fusion: nil demonstrable with peripheral slides

Fixation: **Right** Central **Left** Central

OKR: **N-T** = normal **T-N** = normal

Subject: 7 **DOB:** 24.5.79

Date: 4.7.00

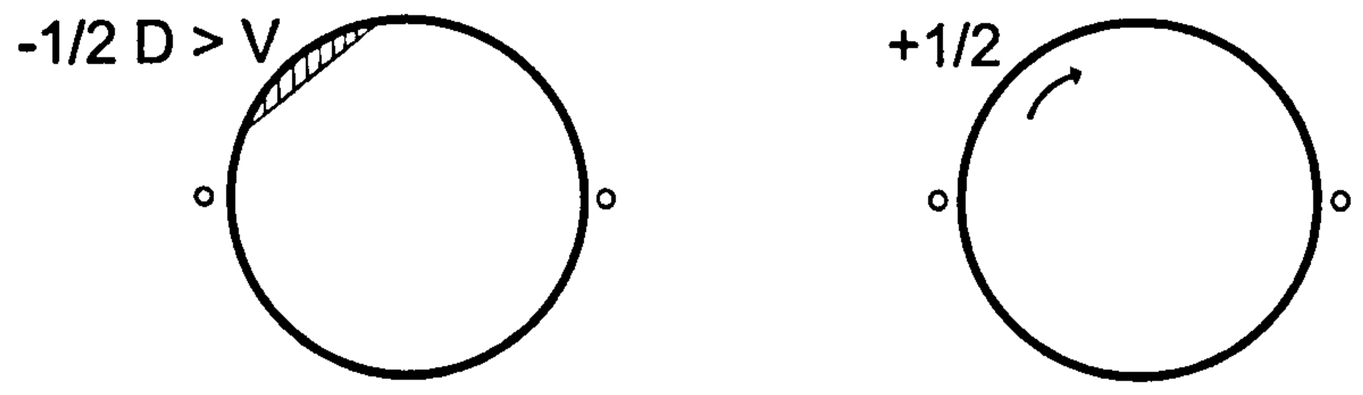
History: Left esotropia noticed at 4 years of age. No glasses, right occlusion at approximately 6 years of age - poor compliance.

Refractive Error: Right +0.50/-0.25 x 90 Left +0.25 nil ordered

Visual Acuity: RE 6/4 LE 6/6 + 1 SN
6/6 6/6 red SN
-0.10 0.00 logMAR

Cover Test: 1/3m slight left esotropia with slight left hypertropia
6m very slight left esotropia with very slight left hypertropia

Ocular Movements:



Convergence: With deviation to 6cm

Binocular Function:

Worth's Lights	**N** ABSV	**D** ABSV
Bagolini	**N** ABSV	**D** ABSV
Pol. 4 dot	**1/3m to 6m** ABSV	
Stereo	**TNO/Frisby/Lang** negative	
Fusion Range:	**N** 4Δ BO - 6Δ BI	**D** 8Δ BO - 6Δ BI

Suppression: **Area:** Nil **Density:** n/a

PCT 1/3m: 10Δ ET 2Δ LHT **1.14m** 10Δ ET 2Δ LHT
6m: 4Δ ET 2Δ LHT

Synoptophore: **Obj. Angle** +4° 2Δ L/R **Subj. Angle** +1° 2Δ L/R
Fusion: +1° 2Δ L/R 6° conv. -3° div. **SV:** Gross

Fixation: **Right** Central **Left** Central

OKR: **N-T** = normal **T-N** = normal

Subject: 8 **DOB:** 24.4.83

Date: 17.7.00

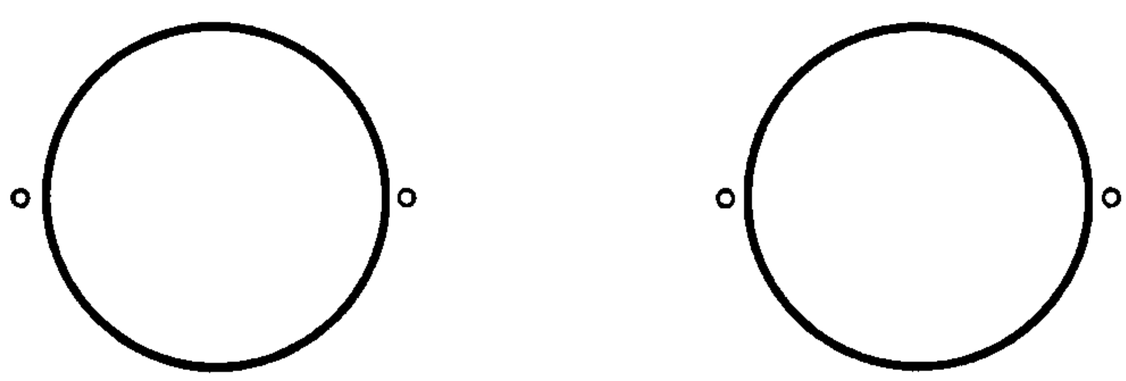
History: No glasses, no symptoms

Refractive Error: RE +0.50, LE +0.50 / +0.75 x 90

Visual Acuity: RE 6/5 LE 6/5 -3 SN
6/6 -3 6/6 -3 red SN
-0.10 -0.10 logMAR

Cover Test: 1/3m very slight left esotropia with very slight left hypertropia
6m very slight left esotropia with very slight left hypertropia

Ocular Movements:



Convergence: With deviation to 6cm

Binocular Function:

Worth's Lights	**N & D** left/alternating suppression
Bagolini	**N** ABSV **D** ABSV
Pol. 4 dot	**1/3m** to 2m ABSV **>2m** left/alternating suppression
Stereo	**TNO/Frisby** negative, **Lang** 200" of arc
Fusion Range:	**N** 10Δ BO - 6Δ BI **D** 4Δ BO - 4Δ BI

Suppression: **Area:** Nil **Density:** n/a

PCT 1/3m: 10Δ ET 3Δ LHT **1.14m** 10Δ ET 2Δ LHT
6m: 10Δ ET 3Δ LHT

Synoptophore: **Obj. Angle** +10° 3Δ L/R **Subj. Angle** +3° 2Δ L/R
Fusion: +2° 2Δ L/R 7° conv. -5° div. **SV:** detailed

Fixation:	**Right** Central steady	**Left** Paramacular nasal steady
OKR:	**N-T** = normal	**T-N** = normal

Subject: 9 **DOB:** 18.11.83

Date: 7.11.02

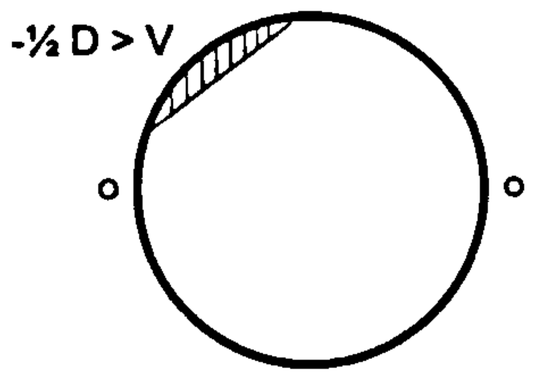
History: Left esotropia noticed at approx 2 years of age. Glasses for hypermetropia from age 2 years and right occlusion for left amblyopia from age 3 years. Surgery for esotropia at age 4.

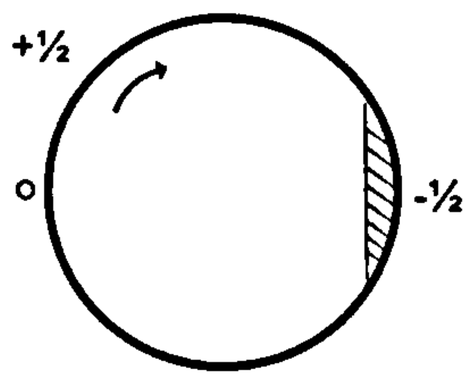
Refractive Error: RE +2.75, LE +3.00/-1.50 x 180

Visual Acuity: RE 6/4 LE 6/36 SN
6/6 6/60 red SN
-1.00 0.60 logMAR

Cover Test:
1/3m slight left exotropia
6m slight+ left exotropia

Ocular Movements:



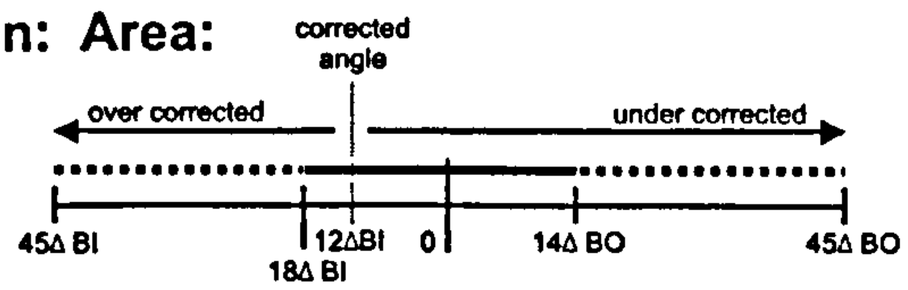


Convergence: With decreasing angle to 10cm then LE diverges with diplopia

Binocular Function:

Worth's Lights	**N & D** left suppression
Bagolini	**N & D** left suppression
Pol. 4 dot	**1/3m to 6m** left suppression
Stereo	**TNO/Frisby/Lang** negative
Fusion Range:	**N & D** nil

Suppression: Area:



Density: filter 14

···· = diplopia
— = suppression

PCT 1/3m: 8Δ XT **1.14m** 8Δ XT
6m: 12Δ XT

Synoptophore: **Obj. Angle** -4° **Subj. Angle** attempts at -2°
Fusion: nil demonstrable with peripheral slides

Fixation: **Right** Central **Left** Parafoveal nasal

OKR: **N-T** = normal **T-N** = normal

Appendix 6

Statistical analysis for Chapter 4

A6.1 Two-factor repeated measures ANOVA for saccade latency – BSV group

Factors

Saccade amplitude	4° / 8°	a
Saccade direction	right / left	d

	DF	SS	MS	F value	P value	Lambda	Power
Subject	4	3531.652	882.913				
a	1	9.941	9.941	0.458	0.5356	0.458	0.082
a*subject	4	86.762	21.691				
d	1	40.613	40.613	1.941	0.2360	1.941	0.187
d*subject	4	83.700	20.925				
a*d	1	0.613	0.613	0.220	0.6637	0.220	0.065
a*d*subject	4	11.150	2.787				

A6.2 Two-factor repeated measures ANOVA for saccade latency – strabismic group

Factors

Saccade amplitude	4° / 8°	a
Saccade direction	right / left	d

	DF	SS	MS	F value	P value	Lambda	Power
Subject	7	6010.419	858.631				
a	1	19.845	19.845	4.529	0.0709	4.529	0.444
a*subject	7	30.675	4.382				
d	1	13.520	13.520	0.757	0.4131	0.757	0.114
d*subject	7	125.040	17.863				
a*d	1	1.051	1.051	0.182	0.6821	0.182	0.066
a*d*subject	7	40.339	5.763				

A6.3 Unpaired t-test difference in saccade latency between BSV and strabismic groups

Hypothesised difference = 0

	Mean diff	DF	t value	p value
BSV/strab	-9.074	11	-1.081	0.3029

A6.4 Two-factor repeated measures ANOVA for saccade gain – BSV group

Factors

Saccade amplitude	4° / 8°	a
Saccade direction	right / left	d

	DF	SS	MS	F value	P value	Lambda	Power
Subject	4	0.010	0.002				
a	1	0.015	0.015	8.457	0.0438	8.457	0.595
a*subject	4	0.007	0.002				
d	1	3.200E-6	3.200E-6	0.004	0.9507	0.004	0.050
d*subject	4	0.003	0.001				
a*d	1	0.001	0.001	1.629	0.2709	1.629	0.165
a*d*subject	4	0.003	0.001				

A6.5 Two-factor repeated measures ANOVA for saccade gain – strabismic group

Factors

Saccade amplitude	4° / 8°	a
Saccade direction	right / left	d

	DF	SS	MS	F value	P value	Lambda	Power
Subject	7	0.064	0.009				
a	1	0.072	0.072	28.290	0.0011	28.290	0.996
a*subject	7	0.018	0.003				
d	1	7.813E-7	7.813E-7	1.589E-4	0.9903	1.589E-4	0.050
d*subject	7	0.005	0.005				
a*d	1	0.002	0.002	3.839	0.0909	3.839	0.386
a*d*subject	7	0.004	0.001				

A6.6 Two-factor repeated measures ANOVA for saccade gain – strabismic group

Factors

Saccade amplitude	4° / 8°	a
direction	to fixing eye / to strabismic eye	d

	DF	SS	MS	F value	P value	Lambda	Power
Subject	7	0.064	0.009				
a	1	0.04	0.004	0.916	0.3704	0.916	0.128
a*subject	7	0.030	0.004				
d	1	0.072	0.072	28.290	0.0011	28.290	0.996
d*subject	7	0.018	0.003				
a*d	1	1.758E-4	1.758E-4	0.195	0.6719	0.195	0.067
a*d*subject	7	0.006	0.001				

A6.7 Unpaired t-test difference in saccade gain between BSV and strabismic groups

a) 4° targets
Hypothesised difference = 0

	Mean diff	DF	t value	p value
BSV/strab	-0.013	11	-0.413	0.6877

a) 8° targets
Hypothesised difference = 0

	Mean diff	DF	t value	p value
BSV/strab	0.027	11	1.178	0.2635

A6.8 Two-factor repeated measures ANOVA for saccade disconjugacy – BSV group

Factors

direction	right / left	d
Saccade amplitude	4° / 8°	a

	DF	SS	MS	F value	P value	Lambda	Power
Subject	4	0.505	0.126				
d	1	2.000E-5	2.000E-5	0.010	0.9246	0.010	0.051
d*subject	4	0.008	0.002				
a	1	0.019	0.019	17.963	0.0133	17.963	0.885
a*subject	4	0.004	0.001				
d*a	1	0.001	0.001	1.250	0.3262	1.250	0.138
d*a*subject	4	0.002	4.000E-4				

A6.9 Two-factor repeated measures ANOVA for saccade disconjugacy – exotropic subjects

Factors

direction	right/ left	d
Saccade amplitude	4° / 8°	a

	DF	SS	MS	F value	P value	Lambda	Power
Subject	2	0.428	0.214				
d	1	0.500	0.500	1.091	0.4059	1.091	0.099
d*subject	2	0.917	0.459				
a	1	0.686	0.686	18.879	0.0491	18.879	0.623
a*subject	2	0.073	0.036				
d*a	1	0.147	0.147	5.330	0.1473	5.330	0.268
d*a*subject	2	0.055	0.028				

A6.10 Two-factor repeated measures ANOVA for saccade disconjugacy – esotropic subjects

Factors

direction	right / left	d
Saccade amplitude	4° / 8°	a

	DF	SS	MS	F value	P value	Lambda	Power
Subject	4	3.870	0.967				
d	1	1.436	1.436	0.475	0.5288	0.475	0.083
d*subject	4	12.107	3.027				
a	1	0.338	0.338	14.593	0.0188	14.593	0.817
a*subject	4	0.093	0.023				
d*a	1	0.084	0.084	0.204	0.6748	0.204	0.064
d*a*subject	4	1.656	0.414				

A6.11 Two-factor repeated measures ANOVA for saccade disconjugacy – esotropic subjects

Factors

direction	to fixing eye / to strabismic eye	d
Saccade amplitude	4° / 8°	a

	DF	SS	MS	F value	P value	Lambda	Power
Subject	4	3.870	0.967				
d	1	1.824	1.824	0.623	0.4742	0.623	0.093
d*subject	4	11.719	2.930				
a	1	0.338	0.338	14.593	0.0188	14.593	0.817
a*subject	4	0.093	0.023				
d*a	1	0.684	0.684	2.593	0.1826	0.684	0.233
d*a*subject	4	1.056	0.264				

A6.12 Unpaired t-test difference in saccade disconjugacy between BSV and exotropic subjects

Saccades towards fixing eye (RE)

a) 4° targets
Hypothesised difference = 0

	Mean diff	DF	t value	p value
BSV/exo	0.257	6	1.784	0.1248

b) 8° targets
Hypothesised difference = 0

	Mean diff	DF	t value	p value
BSV/exo	0.452	6	3.163	0.0195

Saccades towards strabismic eye (RE)

a) 4° targets
Hypothesised difference = 0

	Mean diff	DF	t value	p value
BSV/exo	0.444	6	1.867	0.1111

b) 8° targets
Hypothesised difference = 0

	Mean diff	DF	t value	p value
BSV/exo	1.082	6	3.824	0.0087

A6.13 Unpaired t-test difference in saccade disconjugacy between BSV and esotropic subjects

Saccades towards fixing eye (RE)

a) 4° targets
Hypothesised difference = 0

	Mean diff	DF	t value	p value
BSV/eso	-0.244	8	-0.888	0.4004

b) 8° targets
Hypothesised difference = 0

	Mean diff	DF	t value	p value
BSV/eso	-0.196	8	-0.420	0.6857

Saccades towards strabismic eye (RE)

a) 4° targets
Hypothesised difference = 0

	Mean diff	DF	t value	p value
BSV/eso	-0.478	8	-1.192	0.2674

b) 8° targets
Hypothesised difference = 0

	Mean diff	DF	t value	p value
BSV/eso	-1.170	8	-1.830	0.1047

Appendix 7

Statistical analysis for Chapter 5

A7.1 Statistical analysis of saccade latency without distractors

Two-factor repeated measures analysis of variance

Factors

1. Viewing eye	dominant / non-dominant / both	v
2. Saccade amplitude	4° / 8°	a

	DF	SS	MS	F	P	λ	power
subjects	4	5773.481	1443.370				
a	1	6.902	6.902	0.042	0.8477	0.042	0.053
Error	4	658.184	164.546				
v	2	11.511	5.755	0.145	0.8671	0.290	0.065
Error	8	317.100	39.637				
av	2	44.710	22.355	0.801	0.4818	1.602	0.141
Error	8	223.238	27.905				

A7.2 Comparison of saccade latency in current study with that reported by Walker, Deubel, Schneider and Findlay (1997)

Four one sample t-tests were performed to compare the results of saccade latency in the current study with those reported by Walker, Deubel, Schneider and Findlay (1997).

Saccade latency without distractors

4° targets
Hypothesised mean = 152.0ms

Mean	DF	t-value	p-value
149.764	4	-0.375	0.7269

8° targets
Hypothesised mean = 156.0ms

Mean	DF	t-value	p-value
150.240	4	.-0.730	0.5058

Saccade latency with distractors at fixation

4° targets
Hypothesised mean = 193.5ms

Mean	DF	t-value	p-value
215.928	4	2.008	0.1150

8° targets
Hypothesised mean = 193.5ms

Mean	DF	t-value	p-value
209.190	4	0.990	0.3782

A7.3: Saccade latency with distractor at fixation and without distractor

Three-factor repeated measures analysis of variance

Factors

1. Viewing eye	dominant / non-dominant / both	v
2. Saccade amplitude	4° / 8°	a
3. Distractor	fixation / none	d

	DF	SS	MS	F	P	epsilon
Subjects	4	14954.44	8	3738.612		
a	1	18.073	18.073	0.014	0.9118	
Error	4	5201.707	1300.427			1.00
d	1	40746.895	40746.895	65.000	0.0013	
Error	4	2507.510	626.878			1.00
ad	1	63.469	63.469	0.111	0.7554	
Error	4	2279.965	569.991			1.00
v	2	1131.456	565.728	2.531	0.1407	
Error	8	1787.933	223.492			0.56
av	2	72.914	36.457	0.670	0.5382	
Error	8	435.323	54.415			0.57
dv	2	858.869	429.434	1.949	0.2045	
Error	8	1763.091	220.386			0.78
adv	2	103.464	51.732	1.291	0.3267	
Error	8	320.627	40.078			0.67

A7.4: Saccade latency with distractors ipsilateral or contralateral to target

Four-factor repeated measures analysis of variance

Factors

1. Viewing eye	dominant / non-dominant / both	v
2. Saccade amplitude	4° / 8°	a
3. Distractor side	ipsilateral / contralateral	s
4. Distractor position	2° / 4° / 6° / 8° / 10°	p

	DF	SS	MS	F	P	epsilon
Subjects	4	96522.342	24130.586			
v	2	319.781	159.890	0.535	0.6055	
Error	8	2392.756	299.095			0.92
a	1	230.160	230.160	0.225	0.6598	
Error	4	4087.003	1021.751			1.00
va	2	79.793	39.897	0.582	0.5808	
Error	8	548.478	68.560			0.54
s	1	3861.764	3861.764	58.176	0.0016	
Error	4	265.523	66.381			1.00
vs	2	1005.695	502.847	22.832	0.0005	
Error	8	176.193	22.024			0.68
as	1	101.955	101.955	1.356	0.3090	
Error	4	300.839	75.210			1.00
vas	2	0.997	0.499	0.016	0.9844	
Error	8	253.461	31.683			0.90
p	4	7275.995	1818.999	14.959	0.0000	
Error	16	1945.592	121.599			0.56
vp	8	1003.234	125.404	2.682	0.0223	
Error	32	1496.068	46.752			0.41
ap	4	85.084	21.271	0.272	0.8916	
Error	16	1250.548	78.159			0.37
vap	8	282.396	35.300	0.674	0.7108	
Error	32	1677.090	52.409			0.29
sp	4	430.610	107.653	2.016	0.1406	
Error	16	854.458	53.404			0.53
vsp	8	261.043	32.630	1.219	0.3198	
Error	32	856.648	26.770			0.34
asp	4	274.587	68.647	2.144	0.1224	
Error	16	512.371	32.023			0.36
vasp	8	458.149	57.269	2.117	0.0633	
Error	32	865.617	27.051			0.42

A7.5: Saccade latency with distractors ipsilateral or contralateral to target – dominant / non-dominant eye distractors

Four-factor repeated measures analysis of variance

Factors

1. Viewing eye	dominant / non-dominant	v
2. Saccade amplitude	4° / 8°	a
3. Distractor side	ipsilateral / contralateral	s
4. Distractor position	2° / 4° / 6° / 8° / 10°	p

	DF	SS	MS	F	P	epsilon
Subjects	4	66377.809	16594.452			
v	1	250.455	250.455	0.653	0.4643	
Error	4	1533.651	383.413			1.00
a	1	55.094	55.094	0.56	0.8249	
Error	4	3951.174	987.793			1.00
va	1	5.852	5.852	0.739	0.4385	
Error	4	31.679	7.920			1.00
s	1	1054.920	1054.920	17.890	0.0134	
Error	4	235.862	58.965			1.00
vs	1	5.402	5.402	0.544	0.5018	
Error	4	39.734	9.933			1.00
as	1	70.034	70.034	0.891	0.3986	
Error	4	314.312	78.578			1.00
vas	1	0.951	0.951	0.023	0.8867	
Error	4	165.009	41.252			1.00
p	4	3277.139	819.285	7.746	0.0011	
Error	16	1692.395	105.775			0.43
vp	4	228.916	57.229	1.290	0.3153	
Error	16	709.711	44.357			0.60
ap	4	200.325	50.081	0.433	0.7830	
Error	16	1851.920	115.745			0.36
vap	4	61.364	15.341	0.411	0.7984	
Error	16	597.840	37.365			0.45
sp	4	370.272	92.568	2.754	0.0645	
Error	16	537.816	33.613			0.44
vsp	4	75.433	18.858	0.858	0.5098	
Error	16	351.689	21.981			0.62
asp	4	362.174	90.544	2.218	0.1130	
Error	16	653.042	40.815			0.42
vasp	4	341.334	85.333	3.517	0.0305	
Error	16	388.249	24.266			0.58

A7.6 Statistical analysis of saccade gain without distractors

Two-factor repeated measures analysis of variance

Factors

1. Viewing eye	dominant / non-dominant / both	v
2. Saccade amplitude	4° / 8°	a

	DF	SS	MS	F	P	λ	power
subjects	4	0.041	0.010				
a	1	0.040	0.040	7.789	0.0493	7.789	0.561
Error	4	0.021	0.005				
v	2	0.001	0.0004	0.470	0.6415	0.939	0.102
Error	8	0.007	0.001				
av	2	0.001	0.001	0.201	0.8217	0.403	0.072
Error	8	0.020	0.003				

A7.7 Saccade gain for 4° targets

Three-factor repeated measures analysis of variance

Factors

1. Viewing eye	dominant / non-dominant / both	v
2. Side	ipsilateral / contralateral	s
3. Distractor position	2° / 4° / 6° / 8° / 10°	p

	DF	SS	MS	F	P	epsilon
Subjects	4	0.618	0.155			
v	2	0.538	0.269	13.688	0.0026	
Error	8	0.157	0.020			0.95
s	1	1.030	1.030	48.635	0.0022	
Error	4	0.085	0.021			1.00
vs	2	0.237	0.119	10.292	0.0061	
Error	8	0.092	0.012			0.72
p	4	1.722	0.430	17.890	0.0000	
Error	16	0.385	0.024			0.40
vp	8	0.425	0.053	9.030	0.0000	
Error	32	0.188	0.006			0.28
sp	4	2.020	0.505	19.061	0.0000	
Error	16	0.424	0.026			0.37
vsp	8	0.513	0.064	11.860	0.0000	
Error	32	0.173	0.005			0.33

A7.8 Saccade gain for 4° targets – dominant eye and non-dominant eye

Three-factor repeated measures analysis of variance

Factors

1. Viewing eye	dominant / non-dominant	v
2. Side	ipsilateral / contralateral	s
3. Distractor position	2° / 4° / 6° / 8° / 10°	p

	DF	SS	MS	F	P	epsilon
Subjects	4	0.326	0.081			
v	1	0.053	0.053	3.031	0.1551	
Error	4	0.069	0.017			1.00
s	1	0.310	0.310	21.363	0.0099	
Error	4	0.058	0.015			1.00
vs	1	0.016	0.016	1.066	0.3602	
Error	4	0.058	0.015			1.00
p	4	0.561	0.140	11.699	0.0001	
Error	16	0.192	0.012			0.55
vp	4	0.021	0.005	0.998	0.4372	
Error	16	0.085	0.005			0.36
sp	4	0.638	0.160	10.024	0.0003	
Error	16	0.255	0.016			0.40
vsp	4	0.008	0.002	0.606	0.6642	
Error	16	0.053	0.003			0.61

A7.9 Gain for 8° targets

Three-factor repeated measures analysis of variance

Factors

1. Viewing eye	dominant / non-dominant / both	v
2. Side	ipsilateral / contralateral	s
3. Distractor position	2° / 4° / 6° / 8° / 10°	p

	DF	SS	MS	F	P	epsilon
Subjects	4	0.042	0.011			
v	2	0.082	0.041	2.572	0.1372	
Error	8	0.128	0.016			0.88
s	1	0.385	0.385	24.230	0.0079	
Error	4	0.064	0.016			1.00
vs	2	0.084	0.042	12.237	0.0037	
Error	8	0.027	0.003			0.61
p	4	0.477	0.119	35.798	0.0000	
Error	16	0.053	0.003			0.42
vp	8	0.114	0.014	5.968	0.0001	
Error	32	0.076	0.002			0.29
sp	4	0.650	0.612	37.728	0.0000	
Error	16	0.069	0.004			0.39
vsp	8	0.172	0.022	9.216	0.0000	
Error	32	0.075	0.002			0.36

A7.10 Gain for 8° targets – dominant / non-dominant eye

Three-factor repeated measures analysis of variance

Factors

1. Viewing eye	dominant / non-dominant	v
2. Side	ipsilateral / contralateral	s
3. Distractor position	2° / 4° / 6° / 8° / 10°	p

	DF	SS	MS	F	P	epsilon
Subjects	4	0.048	0.012			
v	1	0.082	0.082	4.157	0.1111	
Error	4	0.079	0.020			1.00
s	1	0.126	0.126	6.009	0.0703	
Error	4	0.084	0.021			1.00
vs	1	0.015	0.015	20.601	0.0105	
Error	4	0.003	0.001			1.00
p	4	0.147	0.037	14.171	0.0000	
Error	16	0.042	0.003			0.33
vp	4	0.009	0.002	1.222	0.3402	
Error	16	0.029	0.002			0.63
sp	4	0.180	0.045	9.774	0.0003	
Error	16	0.074	0.005			0.28
vsp	4	0.005	0.001	0.555	0.6982	
Error	16	0.032	0.002			0.66

Appendix 8

Information sheet

Eye Movement Control in Squint

'You are being invited to take part in a research study. Before you decide it is important for you to understand why the research is being done and what it will involve. Please take time to read the following information carefully and discuss it with friends, relatives and your GP if you wish. Ask us if there is anything that is not clear or if you would like more information. Take time to decide whether or not you wish to take part.

Consumers for Ethics in Research (CERES) publish a leaflet entitled 'Medical Research and You'. This leaflet gives more information about medical research and looks at some questions you may want to ask. A copy may be obtained from CERES, PO Box 1365, London N16 0BW.

What is the purpose of the study?
This study aims to determine how people with squints adapt to use information from their squinting eye. The information collected will lead to a better understanding of squints and their treatment.

What will be involved if I agree to take part in the study?
To study the adaptations occurring in squints various targets will be presented on a large screen, to one or both eyes, eye movements made in response to the targets will be recorded.

Eye movements will be recorded using an eye tracker mounted on a headband. Low powered LED's are used to illuminate the external surface of the eye; the brightness of the reflected beam is measured. As the eye moves the reflection changes and this signal is sent back to a computer for analysis later. There is no contact with the eyes and the light source is invisible.

Each block of eye movement recording will last for 50 seconds and will be preceded by a calibration routine.

The calibration routine will consist of the target moving smoothly across the screen from right to left and back again. You must follow the centre of the target as closely as possible at all times. The calibration lasts for approximately 10 seconds. After the calibration it is important that you keep your head still ready for the eye movement task.

The eye movement task: A small cross target will appear in the centre of the screen. After a variable amount of time it will disappear and reappear at variable distances to the side. At the same time a second larger target may appear on the screen, but this should be ignored at all times. The small target will then return to the central position.

The eye movement recordings will take approximately one hour, breaks will be given throughout testing and you will determine the length of breaks.

Can I withdraw from the study at any time?

Yes. You are free to refuse to join the study and may withdraw at any time. You will receive the same quality of care at the hospital whether you join the study or not.

When and where will the study take place?
We will arrange a time to suit you. The study will take place in the University Department of Ophthalmology and Orthoptics, located on O floor of the Royal Hallamshire Hospital.

What other information will be collected in the study?
Information about your vision and type of squint will be collected in addition to the eye movement recordings.

Will there be effects on my treatment?
No, your participation in the study is not connected to your treatment in any way.

Will the information obtained in the study be confidential?
Any information collected will be treated in confidence, no names will be mentioned in any reports of the study and care will be taken so that individuals cannot be identified from details in reports of the results of the study.

Will anyone else be told about my participation in the study?
No. All information will be treated confidentially.

What if I wish to complain about the way in which this study has been conducted?
If you have *any* cause to complain about *any* aspect of the way in which you have been approached or treated during the course of this study, the normal National Health Service complaints mechanisms are available to you and are not compromised in any way because you have taken part in a research study.

If you have any complaints or concerns please contact the project co-ordinator:

Helen Griffiths Tel: 0114 271 3818

Otherwise you can use the normal University complaints procedure and contact the following person:

Dr A Mallaband, Research & Consultancy Unit, University of Sheffield, 2/4 Palmerston Road, Sheffield, S10 2TE. Tel: 0114 222 1431

Appendix 9

Prism cover test measurements for Chapter 6

Subject	Clinical	Session 1		Session 2		Session 3	
		Before	After	Before	After	Before	After
1	2Δ BI	4Δ BI	2Δ BI	2Δ BI	2Δ BI	2Δ BI	2Δ BI
2	6Δ BO	8Δ BO	6Δ BO	8Δ BO	8Δ BO	6Δ BO	8Δ BO
3	6Δ BO	6Δ BO	6Δ BO	6Δ BO	6Δ BO	6Δ BO	6Δ BO
4	12Δ BI	12Δ BI	12Δ BI	12Δ BI	12Δ BI	12Δ BI	12Δ BI
5	12Δ BO	12Δ BO	12Δ BO	12Δ BO	12Δ BO	12Δ BO	12Δ BO
6	18Δ BI	20Δ BI	18Δ BI	18Δ BI	20Δ BI	20Δ BI	20Δ BI
7	12Δ BO	12Δ BO	12Δ BO	12Δ BO	12Δ BO	12Δ BO	12Δ BO
8	10Δ BO	10Δ BO	12Δ BO	10Δ BO	12Δ BO	10Δ BO	12Δ BO

Appendix 10

Statistical analysis for Chapter 6

A10.1 Two-factor repeated measures ANOVA to test for differences in saccade latency without distractors.

Factors

amplitude	4° / 8°	a
eye	fixing / strabismic / both	e

	DF	SS	MS	F-value	p-value	Lambda	Power
subject	5	5792.309	1158.462				
a	1	331.301	331.301	3.887	0.1057	3.887	0.353
a*subject	5	426.183	85.237				
e	2	193.743	96.872	3.146	0.0871	6.292	0.467
e*subject	10	307.939	30.794				
a*e	2	19.420	9.710	0.540	0.5989	1.080	0.114
a*e*subject	10	179.879	17.988				

A10.2 Three-factor repeated measures ANOVA to test for differences in saccade latency with and without distractors at the original fixation point.

Factors

eye	fixing / strabismic / both	e
amplitude	4° / 8°	a
distractor	present / absent	d

	DF	SS	MS	F-value	p-value	Lambda	Power
subject	5	21032.398	4206.480				
e	2	10173.713	5086.857	49.064	<0.0001	98.127	1.000
e*subject	10	1036.785	103.679				
a	1	0.821	0.821	0.007	0.9347	0.007	0.051
a*subject	5	554.007	110.801				
d	1	28890.872	28890.872	67.274	0.0004	67.274	1.000
d*subject	5	2147.257	429.451				
e*a	2	108.342	54.171	1.213	0.3375	2.427	0.202
e*a*subject	10	446.457	44.646				
e*d	2	10173.713	5086.857	49.064	<0.0001	98.127	1.000
e*d*subject	10	1036.785	103.679				
a*d	1	709.577	709.577	9.997	0.0250	9.997	0.720
a*d*subject	5	354.900	70.980				
a*e*d	2	108.342	54.171	1.213	0.3375	2.427	0.202
a*e*d*subject	10	446.457	44.646				

A10.3 Three-factor repeated measures ANOVA to test for differences in saccade latency with and without distractors at the original fixation point.

Factors

eye	fixing / both	e
amplitude	4° / 8°	a
distractor	present / absent	d

	DF	SS	MS	F-value	p-value	Lambda	Power
subject	5	16478.91	3295.782				
e	1	0.133	0.133	0.001	0.9753	0.001	0.050
e*subject	5	631.671	126.334				
a	1	20.922	20.922	0.315	0.5989	0.315	0.074
a*subject	5	332.153	66.431				
d	1	38815.48	38815.48	88.009	0.0002	88.009	1.000
d*subject	5	2205.208	441.042				
e*a	1	64.241	64.241	0.931	0.3790	0.931	0.121
e*a*subject	5	345.121	69.024				
e*d	1	0.133	0.133	0.001	0.9753	0.001	0.050
e*d*subject	5	631.671	126.334				
a*d	1	654.533	654.533	9.844	0.0257	9.844	0.714
a*d*subject	5	332.438	66.488				
a*e*d	1	64.241	64.241	0.931	0.3790	0.931	0.121
a*e*d*subject	5	345.121	69.024				

A10.4 Two-factor repeated measures ANOVA to test for differences in saccade latency with and without distractors presented to the strabismic eye at the original fixation point.

Factors

amplitude	4° / 8°	a
distractor	present / absent	d

	DF	SS	MS	F-value	p-value	Lambda	Power
subject	5	4958.601	991.720				
a	1	24.000	24.000	0.371	0.5689	0.371	0.078
a*subject	5	323.190	64.638				
d	1	248.970	248.970	3.586	0.1168	3.586	0.330
d*subject	5	347.163	69.433				
d*e	1	99.145	99.145	4.004	0.1018	4.004	0.362
d*e*subject	5	123.797	24.759				

A10.5 Four-factor repeated measures ANOVA to test for differences in saccade latency with distractors ipsilateral or contralateral to the target.

Factors

eye	fixing / strabismic / both	e
amplitude	4° / 8°	a
side	contralateral / ipsilateral	s
distractor position	2° / 4° / 6° / 8° / 10°	p

	DF	SS	MS	F-value	p-value	Lambda	Power
subject	5	46302.541	9260.508				
e	2	5004.167	2502.084	3.535	0.690	7.070	0.516
e*subject	10	7078.272	707.827				
a	1	2509.162	2509.162	11.317	0.0200	11.317	0.772
a*subject	5	1108.622	221.724				
s	1	22294.136	22294.136	103.016	0.0002	103.016	1.000
s*subject	5	1082.074	216.415				
p	4	7393.041	1848.260	12.289	<0.0001	49.155	1.000
p*subject	20	3008.069	150.403				
e*a	2	952.348	476.174	2.436	0.1374	4.872	0.372
e*a*subject	10	1954.630	195.463				
e*s	2	3692.009	1846.004	8.045	0.0083	16.090	0.881
e*s*subject	10	2294.566	229.457				
e*p	8	4464.041	558.005	7.498	<0.0001	59.988	1.000
e*p*subject	40	2976.647	74.416				
a*s	1	109.318	109.318	1.785	0.2391	1.785	0.189
a*s*subject	5	306.205	61.241				
a*p	4	647.003	161.751	2.358	0.0882	9.433	0.568
a*p*subject	20	1371.724	68.586				
s*p	4	1179.233	294.808	3.680	0.0211	14.720	0.791
s*p*subject	20	1602.193	80.110				
e*a*s	2	901.151	450.576	2.584	0.1246	5.167	0.392
e*a*s*subject	10	1743.926	174.393				
e*a*p	8	284.385	35.548	0.567	0.7981	4.538	0.224
e*a*p*subject	40	2506.682	62.667				
e*s*p	8	583.904	72.988	1.426	0.2155	11.412	0.557
e*s*p*subject	40	2046.675	51.167				
a*s*p	4	227.453	56.863	1.603	0.2124	6.413	0.398
a*s*p*subject	20	709.315	35.466				
e*a*s*p	8	535.251	66.906	1.398	0.2272	11.184	0.547
e*a*s*p*subject	40	1914.370	47.859				

A10.6 Four-factor repeated measures ANOVA to test for differences in saccade latency with distractors in the fixing eye and both eyes ipsilateral or contralateral to the target.

Factors

eye	fixing / both	e
amplitude	4° / 8°	a
side	contralateral / ipsilateral	s
distractor position	2° / 4° / 6° / 8° / 10°	p

	DF	SS	MS	F-value	p-value	Lambda	Power
subject	5	38220.581	7644.116				
a	1	2575.067	2575.067	10.608	0.0225	10.608	0.745
a*subject	5	1213.792	242.758				
e	1	97.054	97.054	0.238	0.6461	0.238	0.068
e*subject	5	2036.849	407.370				
s	1	24498.563	24498.563	53.959	0.0007	53.959	1.000
s*subject	5	2270.118	454.024				
p	4	11022.616	2755.654	14.468	<0.0001	57.870	1.000
p*subject	20	3809.414	190.471				
a*e	1	661.543	661.543	3.676	0.0865	9.676	0.706
a*e*subject	5	341.853	68.371				
a*s	1	1.922	1.922	0.027	0.8750	0.027	0.052
a*s*subject	5	350.576	70.115				
a*p	4	429.967	107.492	1.694	0.1908	6.776	0.419
a*p*subject	20	1269.024	63.451				
e*s	1	99.022	99.022	1.266	0.3116	1.266	0.148
e*s*subject	5	390.993	78.199				
e*p	4	165.300	41.325	0.746	0.5720	2.984	0.196
e*p*subject	20	1107.795	55.390				
s*p	4	954.712	238.678	3.167	0.0361	12.668	0.718
s*p*subject	20	1507.304	75.365				
a*e*s	1	605.727	605.727	2.376	0.1839	2.376	0.235
a*e*s*subject	5	1274.939	254.988				
a*e*p	4	73.222	18.305	0.227	0.9202	0.907	0.089
a*e*p*subject	20	1614.681	80.734				
a*s*p	4	315.819	78.955	1.555	0.2250	6.218	0.386
a*s*p*subject	20	1015.746	50.787				
e*s*p	4	312.826	78.207	1.392	0.2724	5.570	0.348
e*s*p*subject	20	1123.295	56.165				
a*e*s*p	4	130.641	32.660	0.735	0.5789	2.940	0.193
a*e*s*p*subject	20	888.726	44.436				

A10.7 Three-factor repeated measures ANOVA to test for differences in saccade latency with distractors ipsilateral or contralateral in the strabismic eye.

Factors

amplitude	4° / 8°	a
side	contralateral / ipsilateral	s
distractor position	2° / 4° / 6° / 8° / 10°	p

	DF	SS	MS	F-value	p-value	Lambda	Power
subject	5	13123.384	2624.677				
a	1	224.899	224.899	0.746	0.4273	0.746	0.107
a*subject	5	1507.607	301.521				
s	1	1388.560	1388.560	9.703	0.0264	9.703	0.708
s*subject	5	715.530	143.106				
p	4	669.165	167.291	3.134	0.0374	12.537	0.712
p*subject	20	1067.507	53.375				
a*s	1	402.820	402.820	4.743	0.0813	4.743	0.417
a*s*subject	5	424.615	84.923				
a*p	4	428.200	107.050	2.152	0.1118	8.610	0.524
a*p*subject	20	994.702	49.735				
s*p	4	495.599	123.900	2.434	0.0810	9.734	0.584
s*p*subject	20	1018.269	50.913				
a*s*p	4	316.245	79.061	2.199	0.1060	8.794	0.534
a*s*p*subject	20	719.214	35.961				

A10.8 Three-factor mixed measures ANOVA to test for differences between strabismic and BSV group for saccade latency with distractor in dominant (fixing) eye at the original fixation.

Factors

group	BSV / strabismic	g
amplitude	4° / 8°	a
distractor	present / absent	d

	DF	SS	MS	F-value	p-value	Lambda	Power
g	1	3411.855	3411.855	2.141	0.1775	2.141	0.248
subject(g)	9	14345.263	1593.198				
a	1	8.178	8.178	0.043	0.8398	0.043	0.054
a*g	1	37.707	37.707	0.200	0.6656	0.200	0.068
a*subject(g)	9	1699.903	188.878				
d	1	31233.495	13233.495	71.246	<0.0001	71.246	1.000
d*g	1	115.985	115.985	0.265	0.6194	0.265	0.074
d*subject(g)	9	3945.518	438.391				
a*d	1	165.785	165.785	0.810	0.3915	0.810	0.123
a*d*g	1	15.019	15.019	0.073	0.7926	0.073	0.057
a*d*subject(g)	9	1841.791	204.643				

A10.9 Three-factor mixed measures ANOVA to test for differences between strabismic and BSV group for saccade latency with distractor in both eyes at the original fixation.

Factors

group	BSV / strabismic	g
amplitude	4° / 8°	a
distractor	present / absent	d

	DF	SS	MS	F-value	p-value	Lambda	Power
g	1	1474.071	1474.071	1.047	0.3330	1.047	0.145
subject(g)	9	12675.293	1408.366				
a	1	133.575	133.757	0.633	0.4467	0.633	0.107
a*g	1	0.192	0.192	0.001	0.9766	0.001	0.050
a*subject(g)	9	1901.555	211.284				
d	1	38984.060	38984.060	144.796	<0.0001	144.796	1.000
d*g	1	85.522	85.522	0.318	0.5868	0.318	0.079
d*subject(g)	9	2423.111	269.235				
a*d	1	465.755	465.755	2.382	0.1572	2.382	0.271
a*d*g	1	109.285	109.285	0.559	0.4738	0.559	0.100
a*d*subject(g)	9	1759.952	195.550				

A10.10 Three-factor mixed measures ANOVA to test for differences between strabismic and BSV group for saccade latency with distractor in non-dominant (strabismic) eye at the original fixation.

Factors

group	BSV / strabismic	g
amplitude	4° / 8°	a
distractor	present / absent	d

	DF	SS	MS	F-value	p-value	Lambda	Power
g	1	157.693	157.693	0.125	0.7318	0.125	0.061
subject(g)	9	11354.929	1261.659				
a	1	30.826	30.826	0.258	0.6240	0.258	0.073
a*g	1	1.110	1.110	0.009	0.9254	0.009	0.051
a*subject(g)	9	1077.107	119.679				
d	1	6638.204	6638.204	68.008	<0.0001	68.008	1.000
d*g	1	3623.925	3623.925	37.127	0.0002	37.127	1.000
d*subject(g)	9	878.481	97.609				
a*d	1	19.926	19.926	0.204	0.6620	0.204	0.069
a*d*g	1	80.325	80.325	0.824	0.3878	0.824	0.125
a*d*subject(g)	9	877.714	97.524				

A10.11 Four-factor mixed measures ANOVA to test for differences between strabismic and BSV group for saccade latency with distractor in dominant (fixing) eye.

Factors

group	BSV / strabismic	g
amplitude	4° / 8°	a
side	contralateral / ipsilateral	s
distractor position	2° / 4° / 6° / 8° / 10°	p

	DF	SS	MS	F-value	p-value	Lambda	Power
g	1	10715.767	10715.767	2.2022	0.1887	2.022	0.237
subject(g)	9	47691.187	5299.021				
a	1	1526.194	1526.194	5.282	0.0471	5.282	0.531
a*g	1	1145.183	1145.183	3.964	0.0777	3.964	0.419
a*subject(g)	9	2300.373	288.930				
s	1	7752.768	7752.768	30.794	0.0004	30.794	0.999
s*g	1	2672.727	2672.727	10.616	0.0099	10.616	0.836
s*subject(g)	9	2265.857	251.762				
p	4	7367.248	1841.812	21.389	<0.0001	85.555	1.000
p*g	4	300.317	75.079	0.872	0.0403	3.488	0.244
p*subject(g)	36	3100.005	86.111				
a*s	1	223.001	223.001	1.684	0.2267	1.684	0.205
a*s*g	1	51.998	51.998	0.393	0.5465	0.393	0.086
a*s*subject(g)	9	1191.904	132.434				
a*p	4	212.105	53.026	0.939	0.4524	3.757	0.262
a*p*g	4	66.885	16.721	0.296	0.8785	1.185	0.107
a*p*subject(g)	36	2032.554	56.460				
s*p	4	401.386	100.346	2.363	0.0713	9.454	0.619
s*p*g	4	88.319	22.080	0.520	0.7215	2.080	0.158
s*p*subject(g)	36	1528.470	42.457				
a*s*p	4	509.678	12.419	2.385	0.0694	0.539	0.624
a*s*p*g	4	388.182	97.046	1.816	0.1471	7.265	0.490
a*s*p*subject(g)	36	1923.556	53.432				

A10.12 Four-factor mixed measures ANOVA to test for differences between strabismic and BSV group for saccade latency with distractor in both eyes.

Factors

group	BSV / strabismic	g
amplitude	4° / 8°	a
side	contralateral / ipsilateral	s
distractor position	2° / 4° / 6° / 8° / 10°	p

	DF	SS	MS	F-value	p-value	Lambda	Power
g	1	12082.398	12082.398	2.266	0.1665	2.266	0.260
subject(g)	9	47996.538	5332.949				
a	1	556.221	556.221	2.713	0.1339	2.713	0.303
a*g	1	0.076	0.076	3.708E-4	0.9851	3.708E-4	0.050
a*subject(g)	9	1845.023	205.003				
s	1	15607.993	15607.993	189.655	<0.0001	189.655	1.000
s*g	1	1141.903	1141.903	13.875	0.0047	13.875	0.923
s*subject(g)	9	740.672	82.297				
p	4	10311.794	2577.949	21.809	<0.0001	87.238	1.000
p*g	4	49.109	12.277	0.104	0.9804	0.415	0.069
p*subject(g)	36	4255.314	118.203				
a*s	1	67.541	67.541	0.758	0.4067	0.758	0.118
a*s*g	1	271.560	274.560	3.080	0.1132	3.080	0.337
a*s*subject(g)	9	802.328	89.148				
a*p	4	78.950	19.737	0.306	0.8717	1.226	0.110
a*p*g	4	273.024	68.256	1.060	0.3904	4.240	0.293
a*p*subject(g)	36	2318.401	64.400				
s*p	4	991.924	247.981	3.871	0.0102	15.484	0.860
s*p*g	4	149.357	37.339	0.583	0.6770	2.332	0.173
s*p*subject(g)	36	2306.133	64.059				
a*s*p	4	26.904	6.726	0.268	0.8964	1.074	0.102
a*s*p*g	4	92.722	23.180	0.925	0.4602	3.700	0.258
a*s*p*subject(g)	36	902.143	25.060				

A10.13 Four-factor mixed measures ANOVA to test for differences between strabismic and BSV group for saccade latency with distractor in non-dominant (strabismic) eye.

Factors

group	BSV / strabismic	g
amplitude	4° / 8°	a
side	contralateral / ipsilateral	s
distractor position	2° / 4° / 6° / 8° / 10°	p

	DF	SS	MS	F-value	p-value	Lambda	Power
g	1	3140.301	3140.301	0.490	0.5016	0.490	0.094
subject(g)	9	57669.984	6407.776				
a	1	189.925	189.925	0.559	0.4736	0.559	0.101
a*g	1	41.475	41.475	0.122	0.7348	0.122	0.061
a*subject(g)	9	3056.298	339.589				
s	1	1792.678	1792.678	20.802	0.0014	20.802	0.987
s*g	1	62.504	62.504	0.725	0.1465	0.725	0.116
s*subject(g)	9	775.597	86.177				
p	4	1176.263	294.066	5.230	0.0020	20.920	0.954
p*g	4	624.894	156.224	2.778	0.0414	11.114	0.703
p*subject(g)	36	2024.159	56.227				
a*s	1	287.034	287.034	3.876	0.0805	3.876	0.411
a*s*g	1	102.431	102.431	1.383	0.2697	1.383	0.176
a*s*subject(g)	9	666.460	74.051				
a*p	4	524.065	131.016	1.997	0.1158	7.988	0.535
a*p*g	4	83.080	20.770	0.317	0.8650	1.266	0.112
a*p*subject(g)	36	2361.974	65.610				
s*p	4	556.845	139.211	3.290	0.0213	13.161	0.788
s*p*g	4	85.276	21.319	0.504	0.7331	2.015	0.154
s*p*subject(g)	36	1523.226	42.312				
a*s*p	4	243.566	60.892	1.760	0.1585	7.038	0.476
a*s*p*g	4	191.565	47.891	1.384	0.2590	5.536	0.379
a*s*p*subject(g)	36	1245.821	34.606				

A10.14 Two-factor repeated measures ANOVA to test for differences in saccade gain without distractors.

Factors

amplitude	4° / 8°	a
eye	fixing / strabismic / both	e

	DF	SS	MS	F-value	p-value	Lambda	Power
subject	5	0.182	0.036				
a	1	0.164	0.164	16.483	0.0097	16.483	0.903
a*subject	5	0.050	0.010				
e	2	0.004	0.002	0.232	0.7971	0.464	0.077
e*subject	10	0.076	0.008				
a*e	2	0.009	0.004	0.620	0.5575	1.240	0.124
a*e*subject	10	0.070	0.007				

A10.15 Three-factor repeated measures ANOVA to test for differences in saccade gain with distractors for 4° targets.

Factors

eye	fixing/ strabismic/ both	e
side	contralateral / ipsilateral	s
distractor position	2° / 4° / 6° / 8° / 10°	p

	DF	SS	MS	F-value	p-value	Lambda	Power
subject	5	2.826	0.565				
p	4	0.725	0.181	3.214	0.0343	12.856	0.725
p*subject	20	1.129	0.056				
s	1	0.225	0.225	24.116	0.0044	24.116	0.975
s*subject	5	0.047	0.009				
e	2	0.067	0.034	4.311	0.0447	8.622	0.607
e*subject	10	0.078	0.008				
p*s	4	2.502	0.626	44.529	<0.0001	178.116	1.000
p*s*subject	20	0.281	0.014				
p*e	8	1.840	0.230	12.868	<0.0001	102.943	1.000
p*e*subject	40	0.715	0.018				
s*e	2	0.406	0.203	12.767	0.0013	27.533	0.988
s*e*subject	10	0.147	0.015				
p*s*e	8	3.600	0.450	38.311	<0.0001	306.489	1.000
p*s*e*subject	40	0.470	0.012				

A10.16 Three-factor repeated measures ANOVA to test for differences in saccade gain with distractors for 8° targets.

Factors

eye	fixing / strabismic / both	e
side	contralateral / ipsilateral	s
distractor position	2° / 4° / 6° / 8° / 10°	p

	DF	SS	MS	F-value	p-value	Lambda	Power
subject	5	0.986	0.197				
p	4	0.752	0.188	13.184	<0.0001	52.737	1.000
p*subject	20	0.285	0.014				
s	1	0.049	0.049	4.718	0.0819	4.718	0.415
s*subject	5	0.052	0.010				
e	2	0.009	0.005	0.829	0.4642	1.659	0.151
e*subject	10	0.056	0.006				
p*s	4	0.687	0.172	14.453	<0.0001	57.810	1.000
p*s*subject	20	0.238	0.012				
p*e	8	0.077	0.010	2.093	0.0595	16.742	0.763
p*e*subject	40	0.185	0.005				
s*e	2	0.096	0.048	8.471	0.0070	16.941	0.898
s*e*subject	10	0.057	0.006				
p*s*e	8	0.467	0.058	9.449	<0.0001	75.590	1.000
p*s*e*subject	40	0.247	0.006				

A10.17 Three-factor repeated measures ANOVA to test for differences in saccade gain with distractors in fixing eye and both eyes for 4° targets.

Factors

eye	fixing / both	e
side	contralateral / ipsilateral	s
distractor position	2° / 4° / 6° / 8° / 10°	p

	DF	SS	MS	F-value	p-value	Lambda	Power
subject	5	1.239	0.248				
e	1	0.370	0.370	4.300	0.0928	4.300	0.385
e*subject	5	0.431	0.086				
s	1	2.308	2.308	75.813	0.0003	75.813	1.000
s*subject	5	0.152	0.030				
p	4	3.551	0.888	39.219	<0.0001	156.877	1.000
p*subject	20	0.453	0.023				
e*s	1	0.060	0.060	0.831	0.1234	1.831	0.192
e*s*subject	5	0.164	0.033				
e*p	4	0.016	0.004	0.429	0.7863	1.714	0.128
e*p*subject	20	0.182	0.009				
s*p	4	2.699	0.675	67.775	<0.0001	271.098	1.000
s*p*subject	20	0.199	0.010				
e*s*p	4	0.099	0.025	1.980	0.1365	7.919	0.485
e*s*p*subject	20	0.249	0.012				

A10.18 Three-factor repeated measures ANOVA to test for differences in saccade gain with distractors in fixing eye and both eyes for 8° targets.

Factors

eye	fixing / both	e
side	contralateral / ipsilateral	s
distractor position	2° / 4° / 6° / 8° / 10°	p

	DF	SS	MS	F-value	p-value	Lambda	Power
subject	5	0.688	0.138				
e	1	0.061	0.061	2.414	0.1810	2.414	0.239
e*subject	5	0.127	0.025				
s	1	0.557	0.557	37.721	0.0017	37.721	0.998
s*subject	5	0.074	0.015				
p	4	0.536	0.134	21.168	<0.0001	84.673	1.000
p*subject	20	0.127	0.006				
e*s	1	0.001	0.001	0.125	0.7385	0.125	0.060
e*s*subject	5	0.043	0.009				
e*p	4	0.003	0.001	0.122	0.9731	0.486	0.070
e*p*subject	20	0.107	0.005				
s*p	4	0.595	0.149	34.629	<0.0001	138.515	1.000
s*p*subject	20	0.086	0.004				
e*s*p	4	0.007	0.002	0.342	0.8467	1.366	0.111
e*s*p*subject	20	0.099	0.005				

A10.19 Two-factor repeated measures ANOVA to test for differences in saccade gain with distractors presented to the strabismic eye for 4° targets.

Factors

side	contralateral / ipsilateral	s
distractor position	2° / 4° / 6° / 8° / 10°	p

	DF	SS	MS	F-value	p-value	Lambda	Power
subject	5	2.041	0.408				
s	1	0.047	0.047	5.524	0.0655	5.524	0.472
s*subject	5	0.042	0.008				
p	4	0.128	0.032	2.310	0.0933	9.240	0.558
p*subject	20	0.278	0.014				
s*p	4	0.055	0.014	1.046	0.4087	4.182	0.265
s*p*subject	20	0.262	0.013				

A10.20 Two-factor repeated measures ANOVA to test for differences in saccade gain with distractors presented to the strabismic eye for 8° targets.

Factors

side	contralateral / ipsilateral	s
distractor position	2° / 4° / 6° / 8° / 10°	p

	DF	SS	MS	F-value	p-value	Lambda	Power
subject	5	0.525	0.105				
s	1	0.019	0.019	7.625	0.0398	7.625	0.603
s*subject	5	0.012	0.002				
p	4	0.018	0.005	0.689	0.6080	2.756	0.183
p*subject	20	0.133	0.007				
s*p	4	0.022	0.006	1.324	0.2954	5.294	0.331
s*p*subject	20	0.085	0.004				

A10.21 Three-factor mixed measures ANOVA to test for differences in saccade gain between the BSV group and the strabismic group with distractors in the dominant (fixing) eye for 4° targets.

Factors

group	BSV / strabismic	g
side	contralateral / ipsilateral	s
distractor position	2° / 4° / 6° / 8° / 10°	p

	DF	SS	MS	F-value	p-value	Lambda	Power
g	1	3.300E-5	3.300E-5	0.001	0.9804	0.001	0.050
subject (g)	9	0.464	0.694				
s	1	0.694	0.694	27.869	0.0005	27.869	0.998
s*g	1	0.146	0.146	5.849	0.0387	5.849	0.575
s*subject(g)	9	0.224	0.025				
p	4	1.375	0.344	32.755	<0.0001	131.019	1.000
p*g	4	0.331	0.083	7.892	0.0001	31.567	0.997
p*subject(g)	36	0.378	0.010				
s*p	4	1.143	0.286	29.662	<0.0001	118.647	1.000
s*p*g	4	0.118	0.029	3.056	0.0288	12.226	0.751
s*p*subject(g)	36	0.347	0.010				

A10.22 Three-factor mixed measures ANOVA to test for differences in saccade gain between the BSV group and the strabismic group with distractors in the dominant (fixing) eye for 8° targets.

Factors

group	BSV / strabismic	g
side	contralateral / ipsilateral	s
distractor position	2° / 4° / 6° / 8° / 10°	p

	DF	SS	MS	F-value	p-value	Lambda	Power
g	1	0.221	0.221	5.048	0.0513	5.048	0.512
subject (g)	9	0.395	0.044				
s	1	0.384	0.384	24.557	0.0008	24.557	0.995
s*g	1	0.015	0.015	0.965	0.3517	0.965	0.137
s*subject(g)	9	0.141	0.016				
p	4	0.335	0.084	17.301	<0.0001	69.205	1.000
p*g	4	0.026	0.006	1.320	0.2810	5.282	0.362
p*subject(g)	36	0.174	0.005				
s*p	4	0.370	0.093	18.593	<0.0001	74.370	1.000
s*p*g	4	0.013	0.003	0.670	0.6173	2.679	0.194
s*p*subject(g)	36	0.179	0.005				

A10.23 Three-factor mixed measures ANOVA to test for differences in saccade gain between the BSV group and the strabismic group with distractors in both eyes for 4° targets.

Factors

group	BSV / strabismic	g
side	contralateral / ipsilateral	s
distractor position	2° / 4° / 6° / 8° / 10°	p

	DF	SS	MS	F-value	p-value	Lambda	Power
g	1	0.031	0.031	0.168	0.6912	0.168	0.065
subject (g)	9	1.642	0.182				
s	1	2.428	2.482	125.909	<0.0001	125.909	1.000
s*g	1	0.015	0.015	0.801	0.3940	0.801	0.122
s*subject(g)	9	0.174	0.019				
p	4	3.447	0.862	47.588	<0.0001	190.353	1.000
p*g	4	0.007	0.002	0.096	0.9829	0.386	0.067
p*subject(g)	36	0.652	0.018				
s*p	4	3.709	0.927	59.289	<0.0001	237.156	1.000
s*p*g	4	0.027	0.007	0.430	0.7859	1.720	0.137
s*p*subject(g)	36	0.563	0.016				

A10.24 Three-factor mixed measures ANOVA to test for differences in saccade gain between the BSV group and the strabismic group with distractors in both eyes for 8° targets.

Factors

group	BSV / strabismic	g
side	contralateral / ipsilateral	s
distractor position	2° / 4° / 6° / 8° / 10°	p

	DF	SS	MS	F-value	p-value	Lambda	Power
g	1	0.153	0.153	2.692	0.1353	2.692	0.301
subject (g)	9	0.513	0.057				
s	1	0.572	0.572	186.170	<0.0001	186.170	1.000
s*g	1	0.006	0.006	1.879	0.2037	1.879	0.223
s*subject(g)	9	0.028	0.003				
p	4	0.674	0.168	40.795	<0.0001	163.181	1.000
p*g	4	0.030	0.007	1.795	0.1512	7.181	0.485
p*subject(g)	36	0.149	0.004				
s*p	4	0.924	0.231	87.425	<0.0001	349.700	1.000
s*p*g	4	0.059	0.015	5.544	0.0014	22.177	0.966
s*p*subject(g)	36	0.095	0.003				

A10.25 Three-factor mixed measures ANOVA to test for differences in saccade gain between the BSV group and the strabismic group with distractors in the non-dominant (strabismic) eye for 4° targets.

Factors

group	BSV / strabismic	g
side	contralateral / ipsilateral	s
distractor position	2° / 4° / 6° / 8° / 10°	p

	DF	SS	MS	F-value	p-value	Lambda	Power
g	1	0.011	0.011	0.040	0.8461	0.040	0.054
subject (g)	9	2.378	0.264				
s	1	0.252	0.252	16.398	0.0029	16.398	0.958
s*g	1	0.044	0.044	2.872	0.1244	2.872	0.318
s*subject(g)	9	0.138	0.015				
p	4	0.448	0.112	8.836	<0.0001	35.344	0.999
p*g	4	0.091	0.023	1.794	0.1515	7.175	0.485
p*subject(g)	36	0.457	0.013				
s*p	4	0.284	0.071	6.433	0.0005	25.734	0.985
s*p*g	4	0.075	0.019	1.691	0.1735	6.764	0.459
s*p*subject(g)	36	0.397	0.011				

A10.26 Three-factor mixed measures ANOVA to test for differences in saccade gain between the BSV group and the strabismic group with distractors in the non-dominant (strabismic) eye for 8° targets.

Factors

group	BSV / strabismic	g
side	contralateral / ipsilateral	s
distractor position	2° / 4° / 6° / 8° / 10°	p

	DF	SS	MS	F-value	p-value	Lambda	Power
g	1	0.034	0.034	0.515	0.4912	0.515	0.097
subject (g)	9	0.603	0.067				
s	1	0.046	0.046	7.483	0.0230	7.483	0.686
s*g	1	0.001	0.001	0.138	0.7186	0.138	0.063
s*subject(g)	9	0.056	0.006				
p	4	0.050	0.012	2.633	0.0501	10.530	0.675
p*g	4	0.039	0.010	2.077	0.1041	8.310	0.554
p*subject(g)	36	0.171	0.005				
s*p	4	0.050	0.013	3.319	0.0206	13.275	0.792
s*p*g	4	0.047	0.012	3.081	0.0279	12.323	0.755
s*p*subject(g)	36	0.136	0.004				

A10.27 d' values for visibility experiment

Signal detection theory was used to calculate an index on accuracy (d') for the response to each distractor position when presented to the dominant, non-dominant or both eyes.

d' = z (yes/signal) – z (yes/non-signal)

Where z (yes/signal) is the standard normal deviate corresponding to the proportion of correct responses (hits) and z (yes/non-signal) is the standard normal deviate corresponding to the proportion of false positives. Z scores of the proportions were obtained from the table of normal distribution.

d' values range from +4 (most accurate) to –4 (least accurate). No correct responses with no false positives would give a d' value of zero.

d' values

a) Subject 1, Exp. 4, Chapter 5

Distractor position	Distractor both eyes	Distractor dominant eye	Distractor non-dominant eye
-10	2.842	2.842	2.842
-8	2.842	2.842	2.124
-6	2.842	2.842	2.842
-4	2.842	2.842	2.842
-2	2.842	2.842	2.842
0	2.842	2.842	2.124
2	2.842	2.842	2.842
4	2.842	2.842	2.842
6	2.842	2.842	2.842
8	2.842	2.124	2.124
10	2.124	2.842	2.124

b) Subject 3, Exp. 4, Chapter 5

Distractor position	Distractor both eyes	Distractor dominant eye	Distractor non-dominant eye
-10	2.564	3.282	2.564
-8	2.564	3.282	3.282
-6	3.282	3.282	3.282
-4	2.564	3.282	3.282
-2	2.564	2.564	2.564
0	3.282	3.282	3.282
2	3.282	2.564	3.282
4	3.282	2.564	2.124
6	2.564	3.282	3.282
8	3.282	3.282	3.282
10	2.124	3.282	2.564

c) Subject 2, Exp. 5, Chapter 6

Distractor position	Distractor both eyes	Distractor fixing eye	Distractor strabismic eye
-10	4.000	4.000	0.718
-8	4.000	4.000	0.000
-6	4.000	4.000	0.000
-4	4.000	3.282	0.000
-2	4.000	4.000	0.000
0	4.000	4.000	0.000
2	3.282	3.282	0.718
4	4.000	4.000	0.000
6	3.282	4.000	0.000
8	4.000	4.000	0.718
10	2.842	3.282	0.000

d) Subject 3, Exp. 5, Chapter 6

Distractor position	Distractor both eyes	Distractor fixing eye	Distractor strabismic eye
-10	3.282	3.282	0.000
-8	3.282	3.282	0.000
-6	3.282	3.282	-0.718
-4	3.282	3.282	-0.718
-2	3.282	3.282	0.000
0	3.282	3.282	-0.718
2	3.282	3.282	-0.718
4	3.282	2.564	0.000
6	3.282	3.282	-0.718
8	2.564	3.282	0.000
10	3.282	2.564	-0.718

e) Subject 4, Exp. 5, Chapter 6

Distractor position	Distractor both eyes	Distractor fixing eye	Distractor strabismic eye
-10	2.842	2.124	-1.158
-8	2.842	2.842	-1.158
-6	2.842	2.842	-1.158
-4	2.842	2.842	-1.158
-2	2.842	2.842	-1.158
0	2.842	2.124	-1.158
2	2.842	2.842	-1.158
4	2.842	2.842	-1.158
6	2.842	2.842	-1.158
8	2.842	2.124	-1.158
10	2.842	2.842	-1.158

f) Subject 5, Exp. 5, Chapter 6

Distractor position	Distractor both eyes	Distractor fixing eye	Distractor strabismic eye
-10	3.282	3.282	0.000
-8	3.282	2.564	-0.718
-6	3.282	3.282	-0.718
-4	3.282	2.564	-0.718
-2	3.282	3.282	-0.718
0	3.282	3.282	-0.718
2	3.282	3.282	-0.718
4	3.282	2.564	-0.718
6	3.282	3.282	-0.718
8	2.564	3.282	0.000
10	3.282	2.564	-0.718

g) Subject 6, Exp. 5, Chapter 6

Distractor position	Distractor both eyes	Distractor fixing eye	Distractor strabismic eye
-10	2.124	2.564	-0.718
-8	2.564	3.282	-0.718
-6	3.282	3.282	-0.718
-4	3.282	3.282	0.000
-2	3.282	3.282	0.000
0	3.282	3.282	-0.718
2	3.282	3.282	-0.718
4	2.564	2.124	-0.718
6	3.282	2.564	-0.718
8	2.564	3.282	-0.718
10	2.124	2.564	0.000

Appendix 11

Statistical analysis for Chapter 7

A 11.1 Subjects with BSV

A11.1.1 Disconjugacy pre- and post adaptation phase – no feedback condition

Centrifugal saccades
Paired t-test
Hypothesized difference = 0
Pre-adaptation phase / post-adaptation phase

Mean diff.	DF	t-value	p-value
-0.009	7	-0.967	0.336

Centripetal saccades
Paired t-test
Hypothesized difference = 0
Pre-adaptation phase / post-adaptation phase

Mean diff.	DF	t-value	p-value
-0.001	7	-0.079	0.9391

A11.1.2 Disconjugacy pre- and post adaptation phase – feedback condition

Difference in effect between feedback dominant eye (subjects 1-4) or non-dominant eye (subjects 5-8)
Unpaired t-test
Hypothesized difference = 0
Convergent disparity
feedback dom/ feedback non-dom

Mean diff.	DF	t-value	P-value
0.050	6	1.002	0.3552

Divergent disparity
feedback dom/ feedback non-dom

Mean diff.	DF	t-value	P-value
-0.006	6	-0.092	0.9301

Difference between pre and post-adaptation phase following feedback gain (all 8 subjects)

Convergent disparity
Paired t-test
Hypothesized difference = 0
pre-adaptation phase / post-adaptation phase

Mean diff.	DF	t-value	p-value
-0.145	7	-5.784	0.0007

Divergent disparity
Paired t-test
Hypothesized difference = 0
pre- adaptation phase / post-adaptation phase

Mean diff.	DF	t-value	p-value
-0.133	7	-4.386	0.0032

Difference in effect between convergent and divergent disparity
Paired t-test
Hypothesized difference = 0
change in disconjugacy conv. disparity / change in disconjugacy div. disparity

Mean diff.	DF	t-value	p-value
0.013	7	0.574	0.5837

A11.2 Subjects with strabismus

The results of feedback during the adaptation phase were highly variable amongst subjects with some showing adaptation appropriate in direction for the induced disparity whilst others demonstrated adaptations in the opposite direction. To determine whether individual strabismic subject's results were significantly different from the group of subjects with BSV individual z scores were calculated. The probability of results being the same as the normal BSV subjects could then be examined.

z scores were calculated as follows:

$$z = \frac{x - \mu}{\sigma}$$

x = Mean change in disconjugacy following feedback of individual strabismic subject

μ = Mean change in disconjugacy of BSV group

σ = Standard deviation of BSV group

z scores were then converted to p using the table of normal distribution (2 tailed).

Subj	Fixing eye				Strabismic eye			
	Convergent		Divergent		Convergent		Divergent	
	z score	p value	z score	p value	z score	p value	z score	p value
1	-3.87	<0.001	-3.86	<0.001	-0.65	<0.001	-5.53	<0.001
2	0.25	0.802	0.01	1.000	-1.41	0.158	1.02	0.308
4	-0.35	0.726	1.30	0.194	1.59	0.112	-0.45	0.652
5	-1.37	0.170	-1.27	0.204	-2.89	0.004	-1.12	0.262
6	-6.58	<0.001	-3.05	0.002	-1.55	0.122	1.53	0.126
9	0.70	0.484	-0.13	0.896	4.30	<0.001	2.19	0.028

Table A11.1: z scores and p values (2 tailed) for individual strabismic subjects. The results of the change in disconjugacy in the pre and post adaptation phases for feedback to the fixing eye and strabismic eye to induced convergent and divergent disparity are compared for significant differences from the mean and SD of the normal BSV group. None significant values indicate a response comparable to the normal BSV group response, significant values represent responses significantly different from those found in normal BSV.

Subject	Fixing eye		Strabismic eye	
	Convergent	Divergent	Convergent	Divergent
1	***	***	***	***
2	-	-	-	-
4	-	-	-	-
5	-	-	**	-
6	***	**	-	-
9	-	-	***	*

Table A11.2: Summary of significance levels of z scores for individual strabismic subjects. Conditions where the results were significantly different from the control group are represented as follows: * = $p \leq 0.05$; ** = $p \leq 0.01$; *** = $p \leq 0.001$. Where there is no significant difference from the control group the symbol - is used representing no significant difference from the BSV subjects. Symbols in red represent adaptation in an appropriate direction for the induced disparity, black represents adaptation in an inappropriate direction.

Appendix 12

Time course of adaptation

A12.1 Individual data of BSV subjects

Figures A12.1 and A12.2 show the saccade gain disconjugacy during the adaptation phase plotted against time for each of the BSV subjects. All subjects, with the exception of subject 3 for convergent disparity and subject 7 for divergent disparity, show a similar pattern. Saccade gain disconjugacy is seen to increase rapidly over the first 6 runs (equivalent to approximately 5 minutes) and then continuing to increase at a slower rate levelling out in most cases by approximately run 14. Subject 3 for convergent disparity shows a slightly different response in that the largest increase occurred in the first 4 runs as feedback was applied, this was followed by a gradual decrease in the response. Subject 7 showed a large increase in disconjugacy in the first run following application of feedback, this remained at a similar level throughout the adaptation phase.

A12.2 Individual data of strabismic subjects

Figures A12.3 and A12.4 show disconjugacy during the adaptation phase plotted against time for each of the three strabismic subjects who adapted in an appropriate direction for the induced disparity. Figure A12.5 shows the mean saccade gain disconjugacy over the time course of the adaptation phase for each of the two subjects from the strabismic group who adapted in an inappropriate direction. With feedback applied to the fixing eye subject 1 showed an immediate inappropriate change in disconjugacy during run 5 and this remained throughout the adaptation phase whereas subject 6 initially made changes in disconjugacy appropriately for the disconjugacy, but reversed this response in run 8 and continued to show increasing inappropriate direction disconjugacy. With feedback applied to the strabismic eye subject 1 had a similar response whereas subject 6 now showed disconjugacy appropriate in direction for the induced disparity.

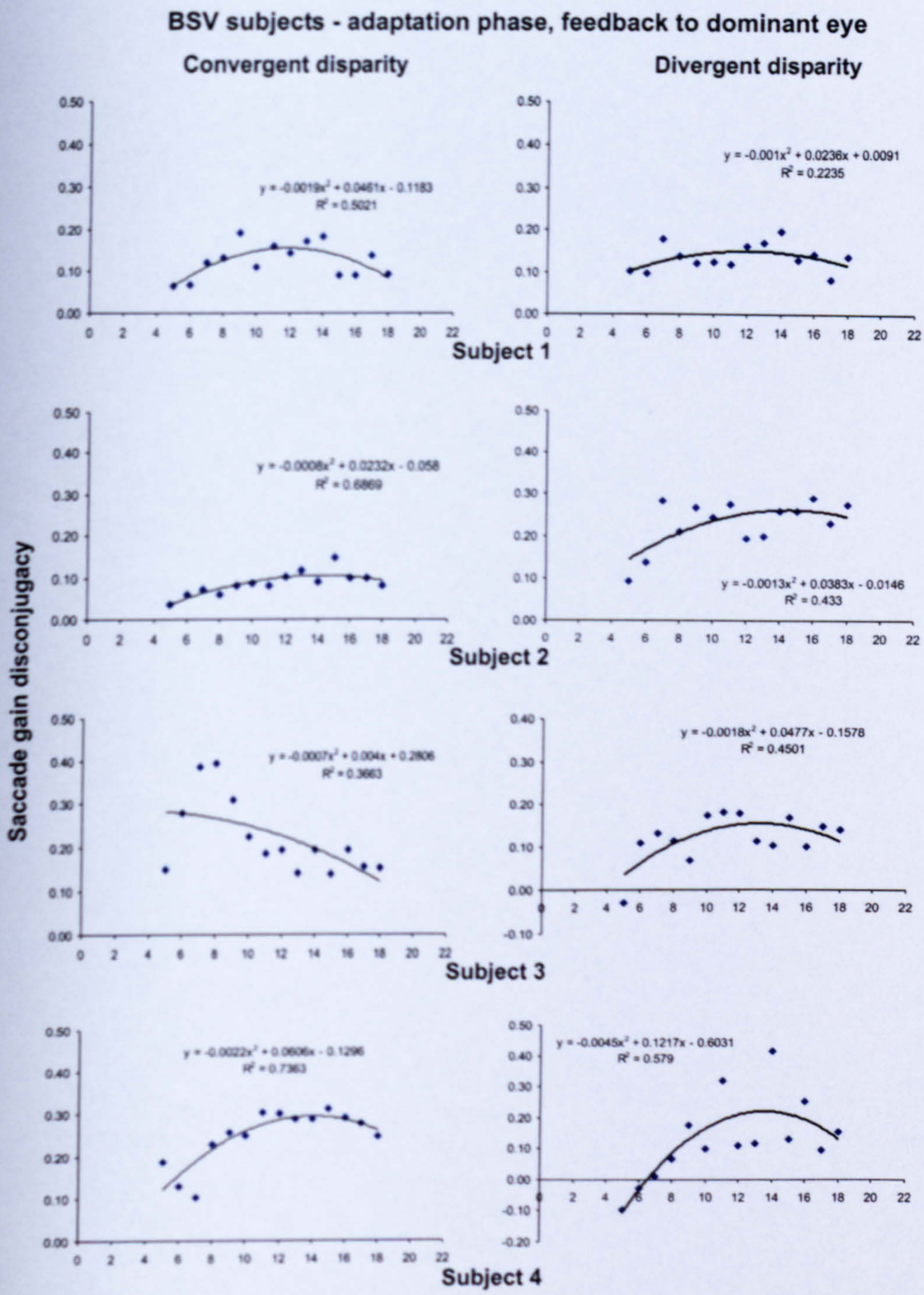


Figure A12.1: Saccade gain disconjugacy during the adaptation phase in four BSV subjects with feedback applied to the dominant eye. Convergent disparity, shown on the left and divergent disparity on the right. NB: Axes shown are not equal in all graphs due to differences in response of some subjects.

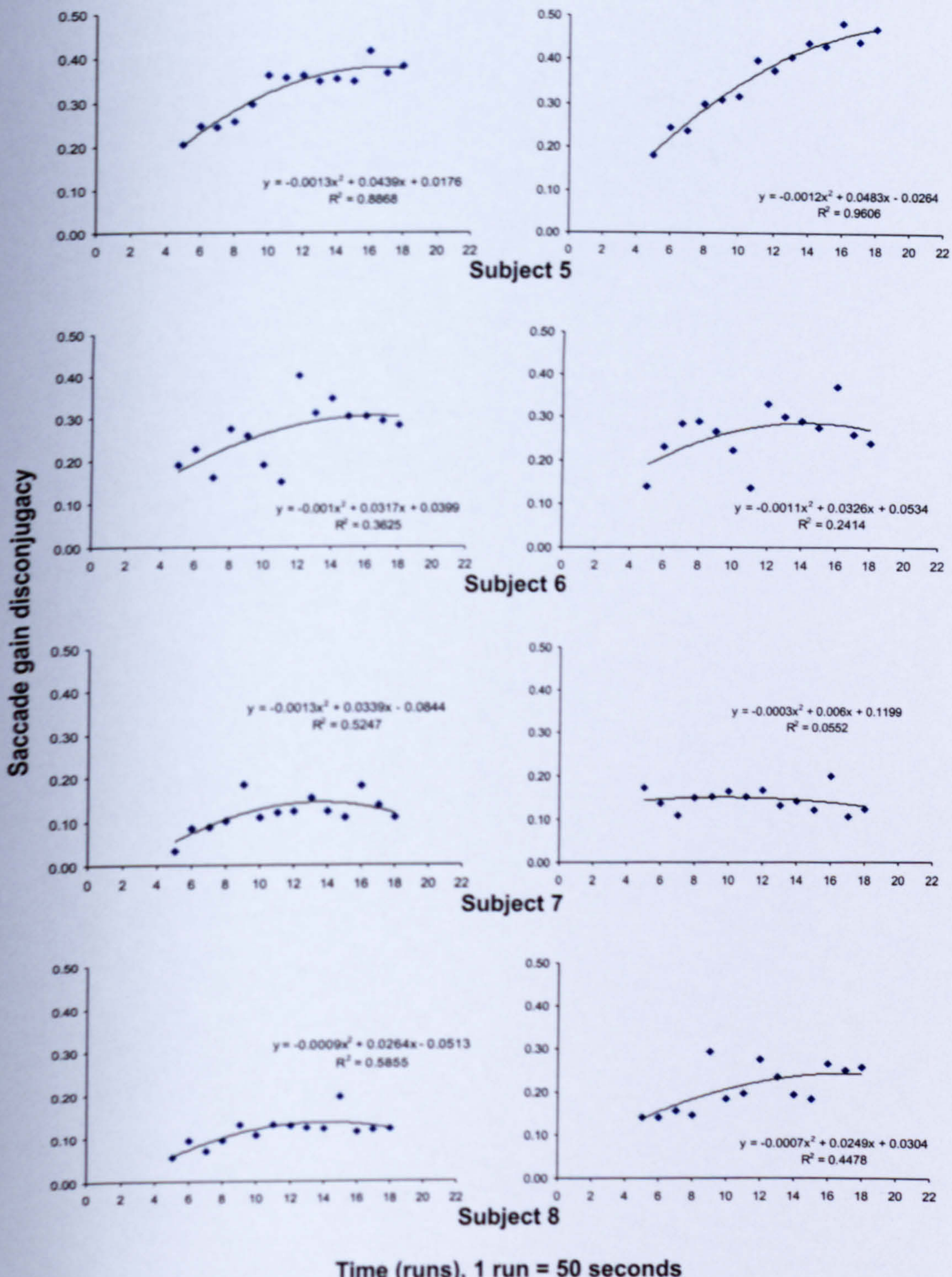


Figure A12.2: Saccade gain disconjugacy during the adaptation phase in four BSV subjects with feedback applied to the non-dominant eye. Convergent disparity shown on the left and divergent disparity on the right.

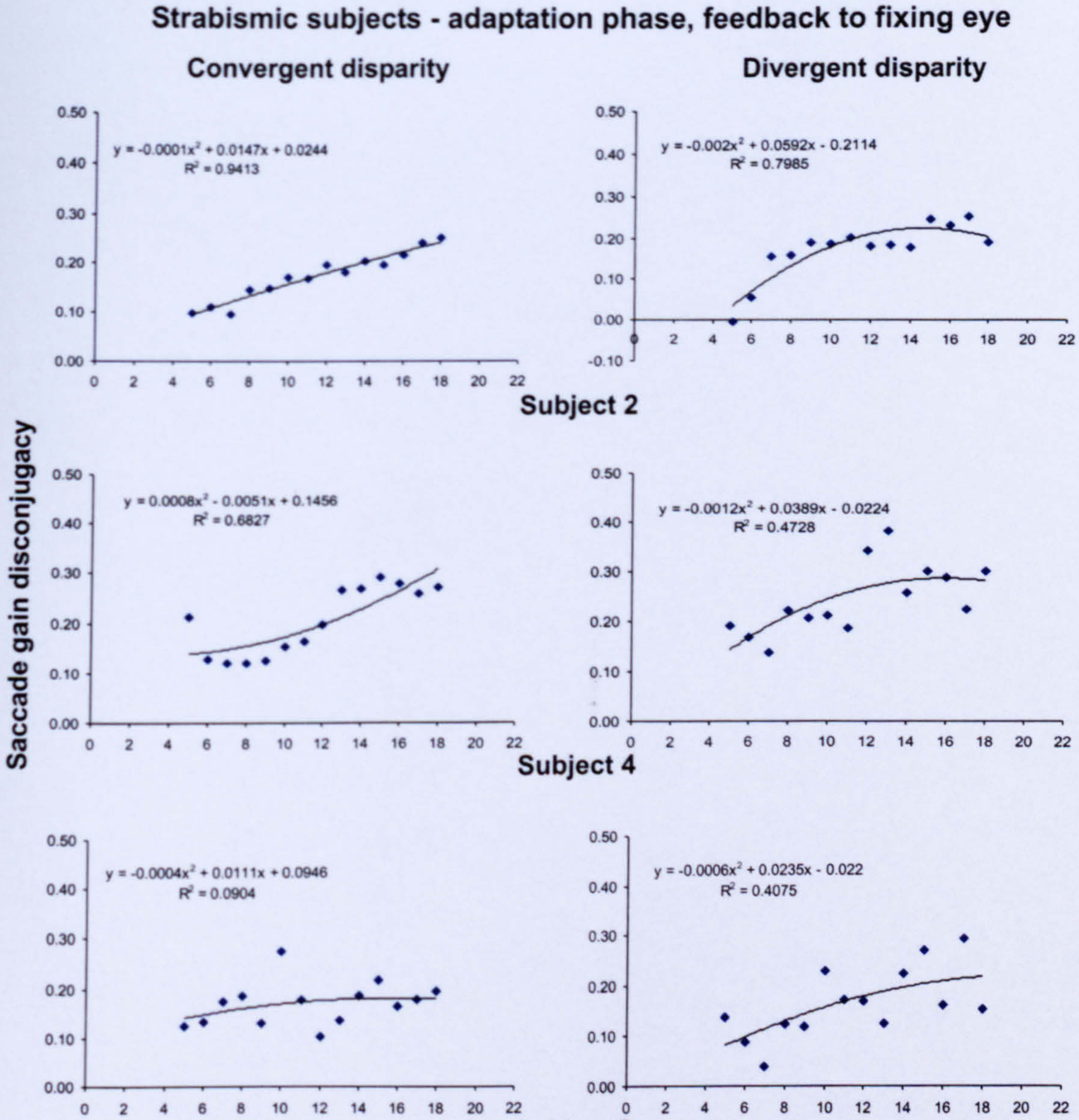


Figure A12.3: Saccade gain disconjugacy during the adaptation phase in three strabismic subjects with feedback applied to the fixing eye. Data shown for subjects 2, 4 and 9 who showed saccade gain disconjugacy in an appropriate direction for the induced disparity. Convergent disparity, shown on the left and divergent disparity on the right. NB: Axes shown are not equal in all graphs due to differences in response of some subjects.

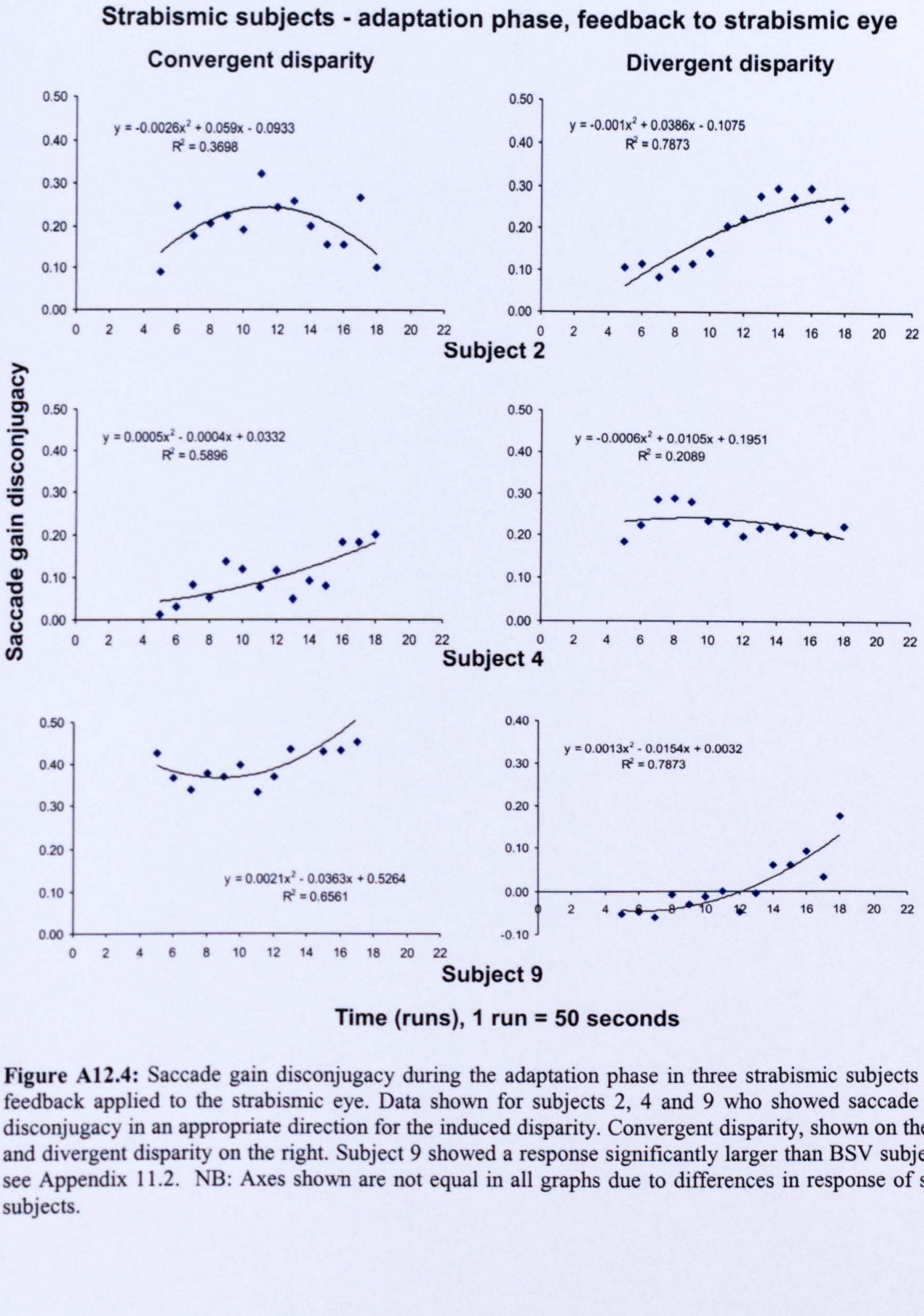
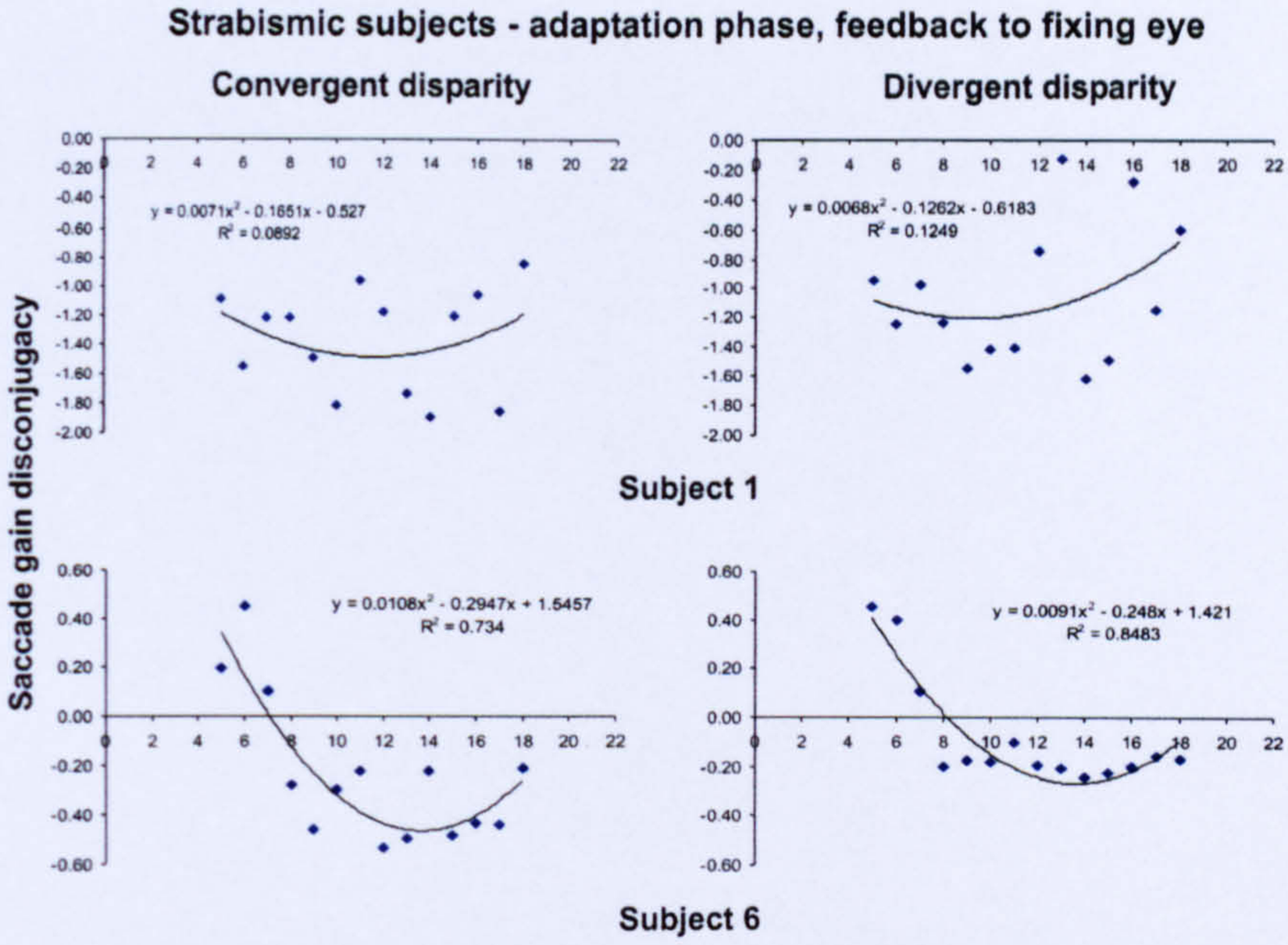


Figure A12.4: Saccade gain disconjugacy during the adaptation phase in three strabismic subjects with feedback applied to the strabismic eye. Data shown for subjects 2, 4 and 9 who showed saccade gain disconjugacy in an appropriate direction for the induced disparity. Convergent disparity, shown on the left and divergent disparity on the right. Subject 9 showed a response significantly larger than BSV subjects - see Appendix 11.2. NB: Axes shown are not equal in all graphs due to differences in response of some subjects.

a)



b)

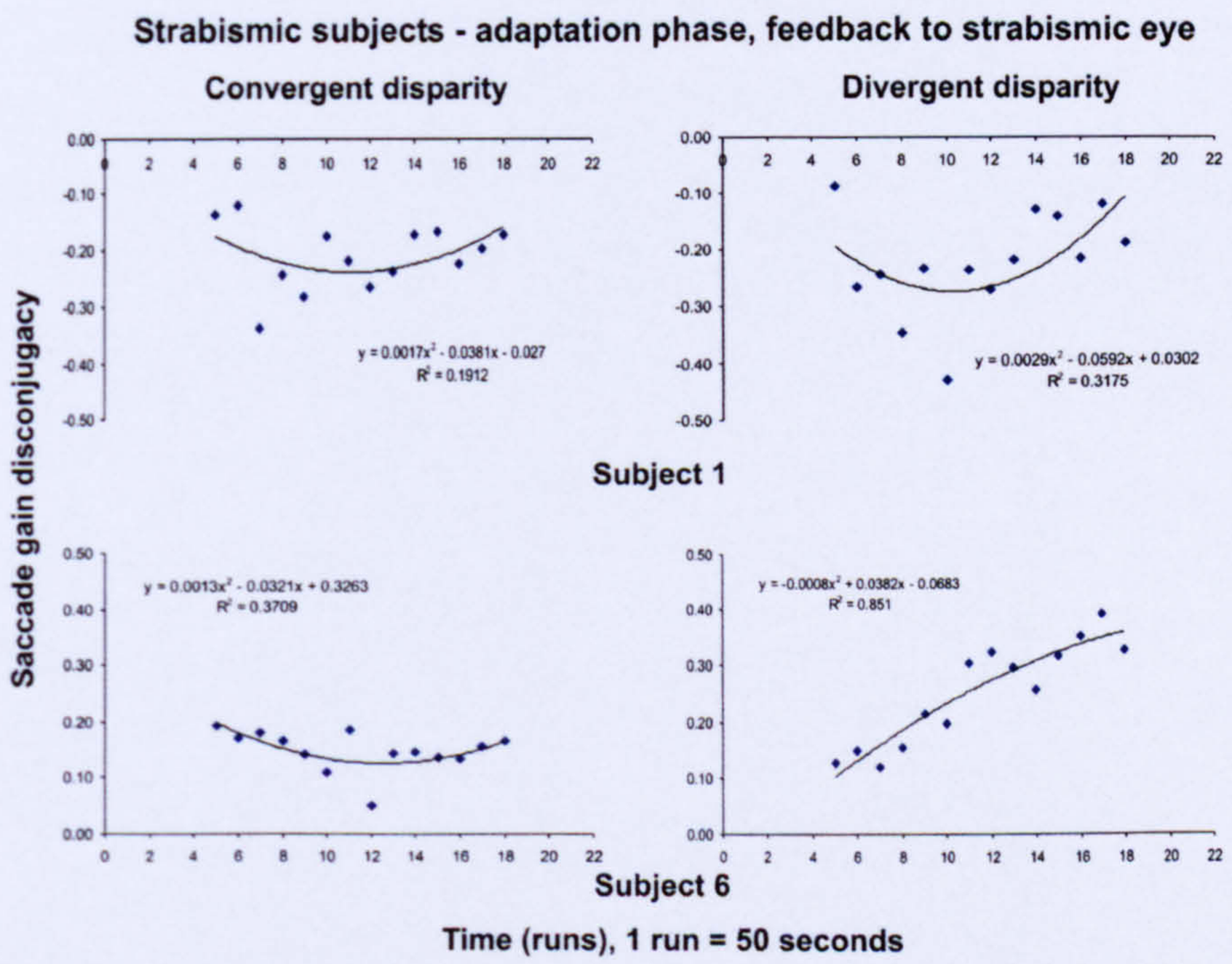


Figure A12.5: a) Saccade gain disconjugacy during the adaptation phase in two strabismic subjects with feedback applied to the fixing eye. Data shown for subjects 1 and 6 who showed saccade gain disconjugacy in an inappropriate direction for the induced disparity. **b)** Saccade gain disconjugacy during the adaptation phase in two strabismic subjects with feedback applied to the strabismic eye. Data shown for subjects 1 and 6, subject 1 shows inappropriate adaptation but subject 6 now shows adaptation appropriate for the disparity Convergent disparity shown on the left and divergent disparity on the right. NB: Axes shown are not equal in all graphs due to differences in response of some subjects.

A12.3 Mean data of BSV subjects and strabismic subjects

Figures A12.6 and A12.7 show the adaptation phase (runs 5 to 18) with polynomial curves fitted to the data. The mean data of three subjects with BSV and three subjects with strabismus who adapted appropriately are shown. Trend analyses (Winer, 1962) were performed on the data to determine whether there were any differences in the adaptation curves. This required an equal number of subjects to be compared in each group. The three BSV subjects who showed similar adaptation curves were selected for analysis, i.e. with feedback to the dominant eye subjects 1, 2 and 4; with feedback to the non-dominant eye subjects 5, 6 and 8.

Four separate two-factor repeated measures trend analyses were performed on the data from each group to determine whether there was a difference between adaptation to convergent and divergent disparity. Details of the trend analyses are shown in Appendix 12.4.1.

With feedback to the dominant eye these showed no significant linear trend [$F(1,2)=3.565$, $p>0.05$] for the BSV group but a significant linear fit to the data strabismic group [$F(1,2)=27.297$, $p<0.05$]. There was no significant difference between the linear fit for convergent and divergent disparity for the BSV group [$F(1,2)=2.535$, $p>0.05$] or strabismic group [$F(1,2)=0.131$, $p>0.05$]. There was also no significant quadratic relationship for the BSV group [$F(1,2)=7.847$, $p>0.05$] or for the strabismic group [$F(1,2)=17.614$, $p>0.05$]. This was not significantly different for convergent and divergent disparity for the BSV group [$F(1,2)=0.430$, $p>0.05$] or strabismic group [$F(1,2)=4.681$, $p>0.05$]. With feedback to the non-dominant eye these showed no significant linear trend [$F(1,2)=9.736$, $p>0.05$] for the BSV group but a significant linear fit to the data strabismic group [$F(1,2)=20.760$, $p<0.05$]. There was no significant difference between the linear fit for convergent and divergent disparity for the BSV group [$F(1,2)=0.649$, $p>0.05$] or strabismic group [$F(1,2)=0.583$, $p>0.05$]. There was a significant quadratic relationship for the BSV group [$F(1,2)=77.423$, $p<0.05$] but not for the strabismic group [$F(1,2)=0.704$, $p>0.05$]. This was not significantly different for convergent and divergent disparity for the BSV group [$F(1,2)=0.264$, $p>0.05$] or strabismic group [$F(1,2)=0.215$, $p>0.05$]. This shows that the response of disconjugate adaptation is not significantly different for convergent and divergent disparities for both groups of subjects.

Four separate two-factor mixed measures trend analyses were performed on the data to determine whether there was a difference in the adaptation phases between the two groups with feedback to the dominant eye or non-dominant eye for convergent and divergent disparity. Details of the trend analyses are shown in Appendix 12.4.2.

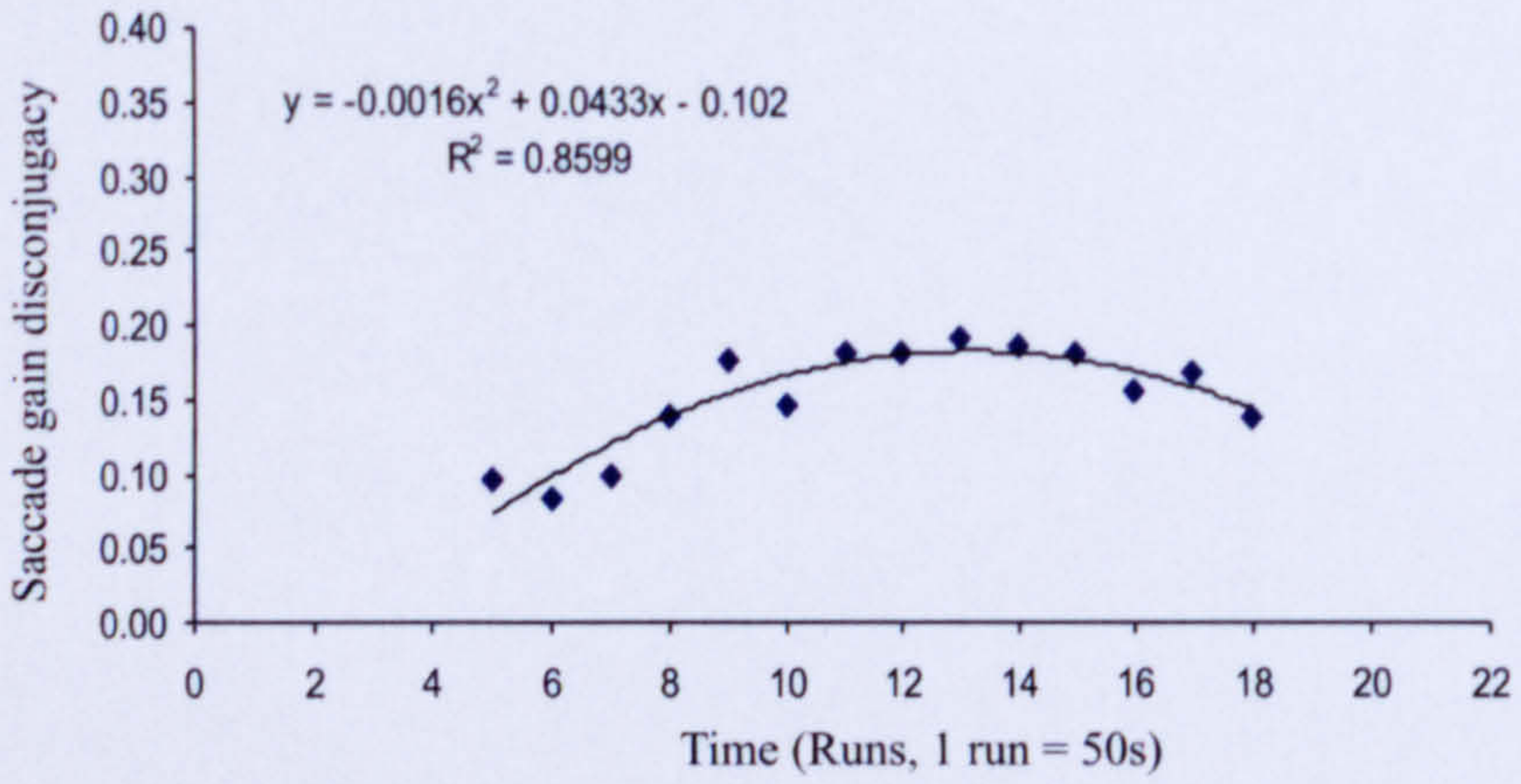
With feedback to the dominant eye inducing convergent disparity there was a significant linear fit to the data [$F(1,6)=11.016$, $p<0.05$] and no significant difference between the groups [$F(1,4)=0.881$, $p>0.05$]. There was also a significant quadratic relationship [$F(1,6)=19.731$, $p<0.01$] which was significantly different between the groups [$F(1,4)=11.321$, $p<0.05$]. With feedback to the dominant eye inducing divergent disparity there was a significant linear fit to the data [$F(1,6)=16.345$, $p<0.01$] and no significant difference between the groups [$F(1,4)=0.183$, $p>0.05$]. There was also a significant quadratic relationship [$F(1,6)=8.744$, $p<0.05$] and no significant difference between the groups [$F(1,4)=0.688$, $p>0.05$]. With feedback to the non-dominant eye inducing convergent disparity there was a significant linear fit to the data [$F(1,6)=6.349$, $p<0.05$] and no significant difference between the groups [$F(1,4)=2.067$, $p>0.05$].

There was no significant quadratic relationship [$F(1,6)=1.286$, $p>0.05$] which was not significantly different between the groups [$F(1,4)=0.454$, $p>0.05$]. With feedback to the non-dominant eye inducing divergent disparity there was a significant linear fit to the data [$F(1,6)=7.335$, $p<0.05$] and no significant difference between the groups [$F(1,4)=0.015$, $p>0.05$]. There was also a significant quadratic relationship [$F(1,6)=99.734$, $p<0.001$] and no significant difference between the groups [$F(1,4)=1.557$, $p>0.05$]. This shows that the time course of adaptation in response to feedback to either eye was not significantly different in the two groups for either types of disparity.

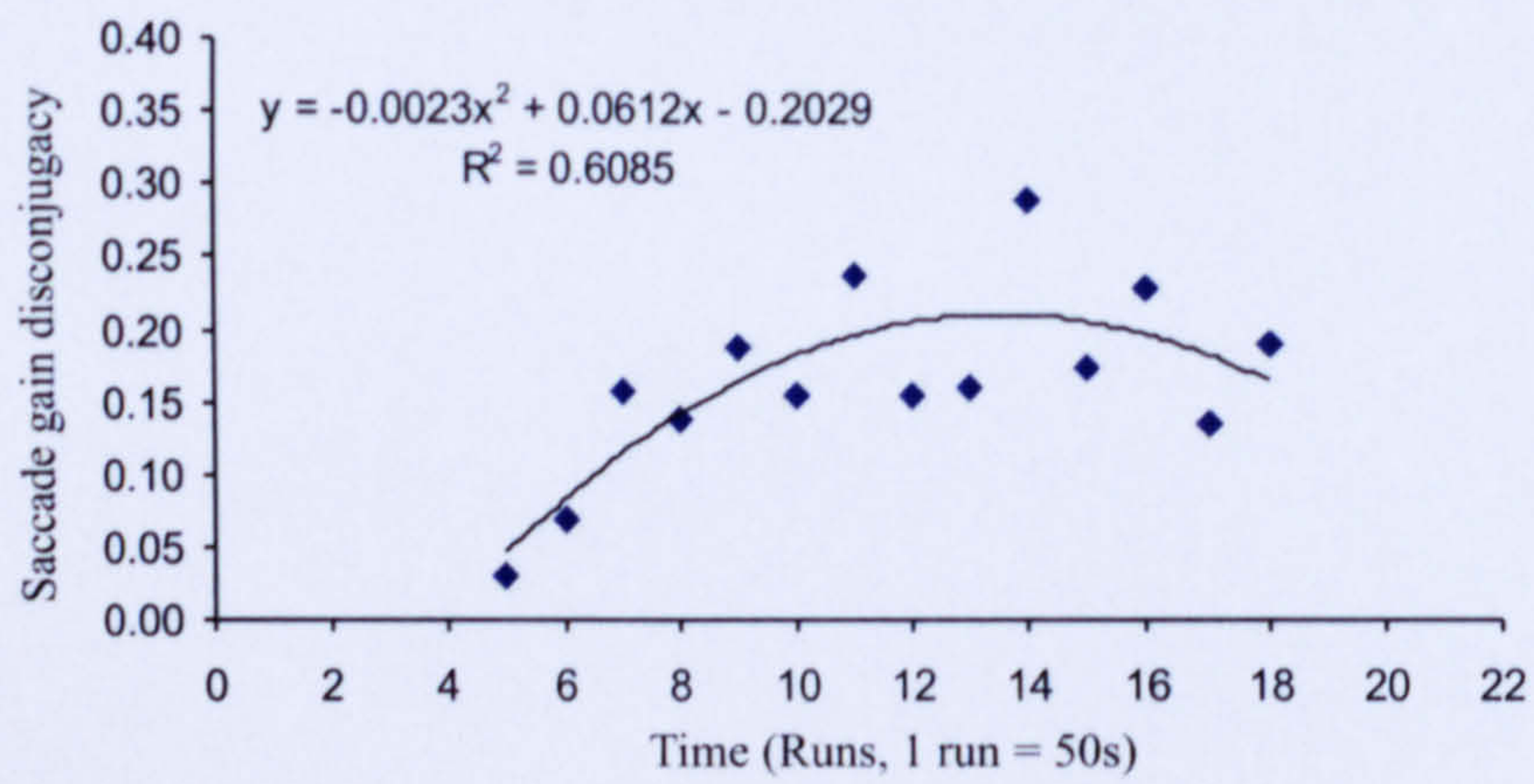
To further test for differences in the rate of adaptation between groups two three-factor mixed measures ANOVA's were calculated, one for feedback to the dominant eye and one for non-dominant eye. The three factors were group (BSV or strabismic), disparity (convergent or divergent) and time (run 5 to run 18). There was no significant difference between groups [dominant eye $F(1,4)=1.297$, $p>0.05$; non-dominant eye $F(1,4)=1.600$, $p>0.05$] or interactions between group and the other factors. The only significantly different factor was time, [dominant eye $F(13,52)=6.384$, $p<0.0001$; non-dominant eye $F(13,52)=6.778$, $p<0.0001$]. This shows that the response to feedback in the two groups was not significantly different under any of the test conditions. Details of the ANOVA are shown in Appendix 12.5.

Adaptation phase - feedback to dominant eye

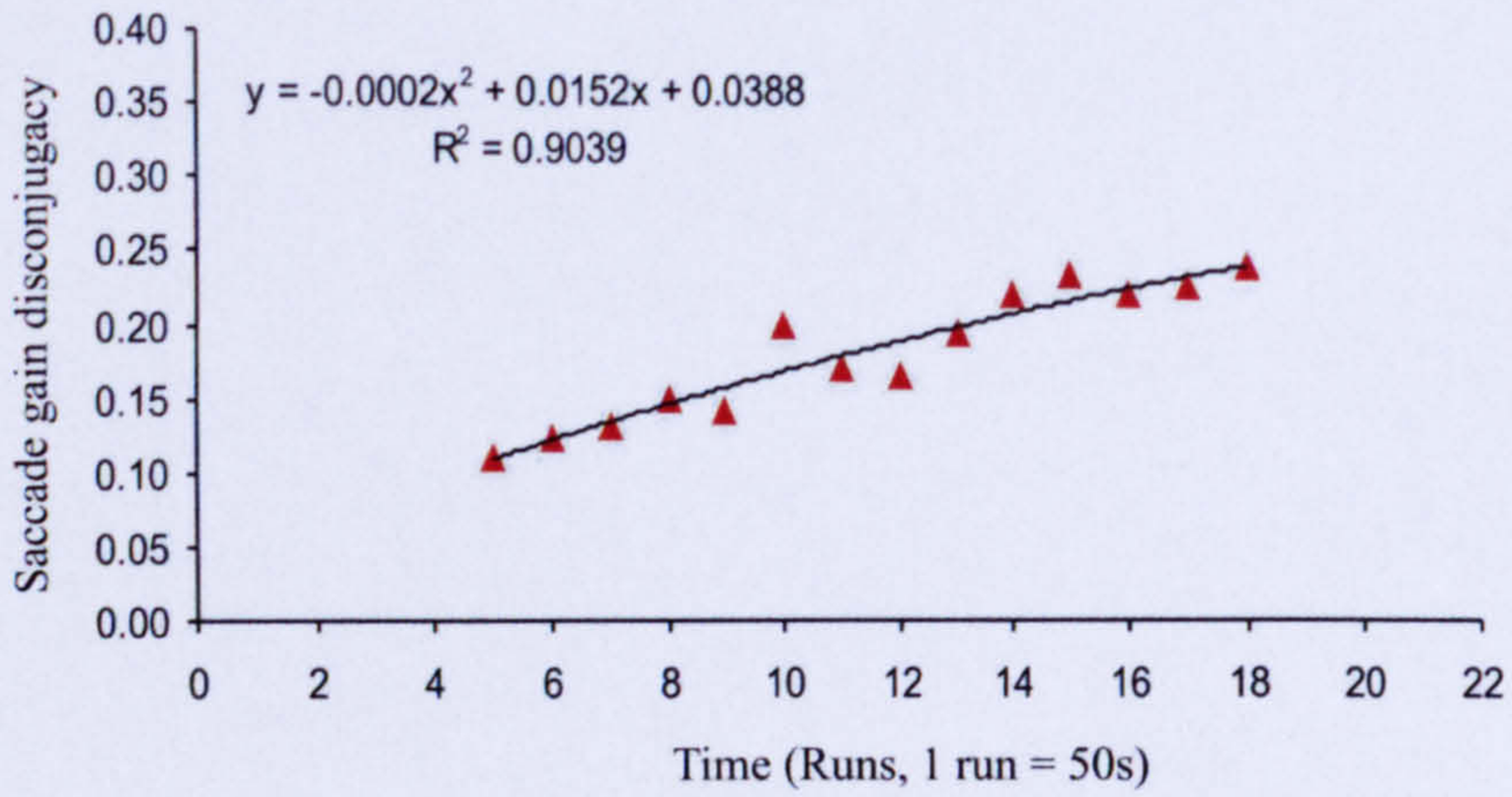
a) BSV subjects - convergent disparity



b) BSV subjects - divergent disparity



c) Strabismic subjects (appropriate adaptors) - convergent disparity



d) Strabismic subjects (appropriate adaptors) divergent disparity

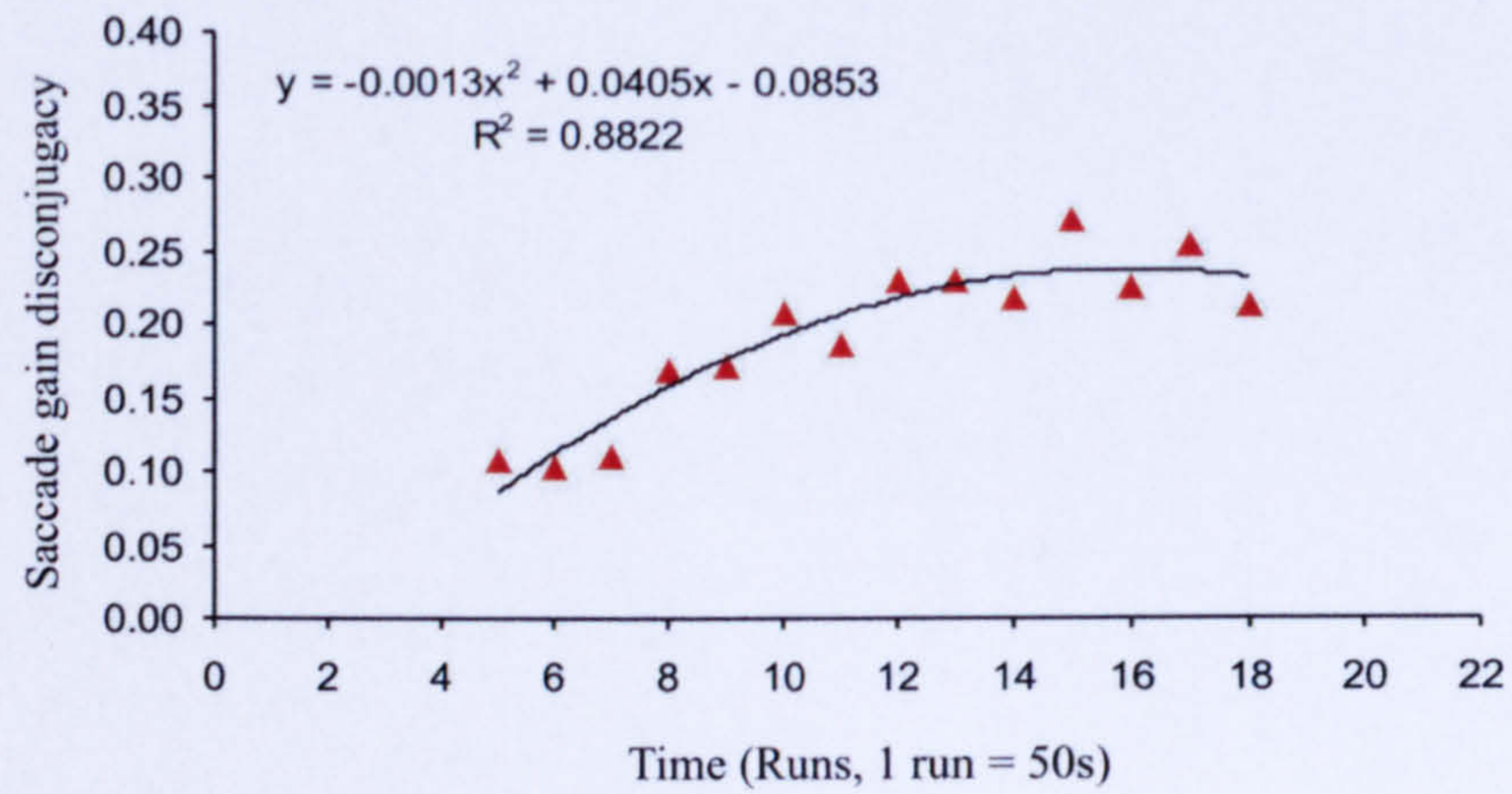
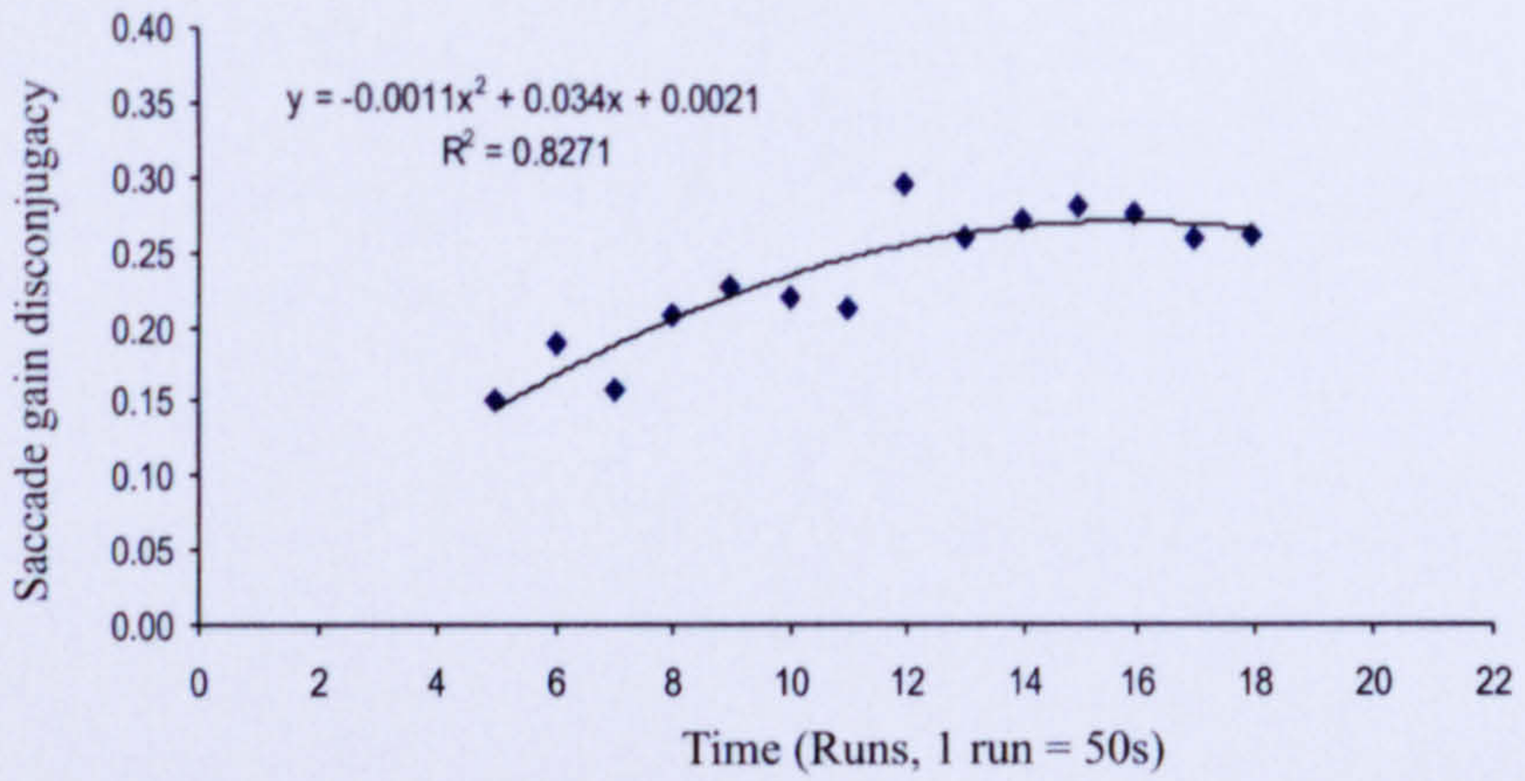


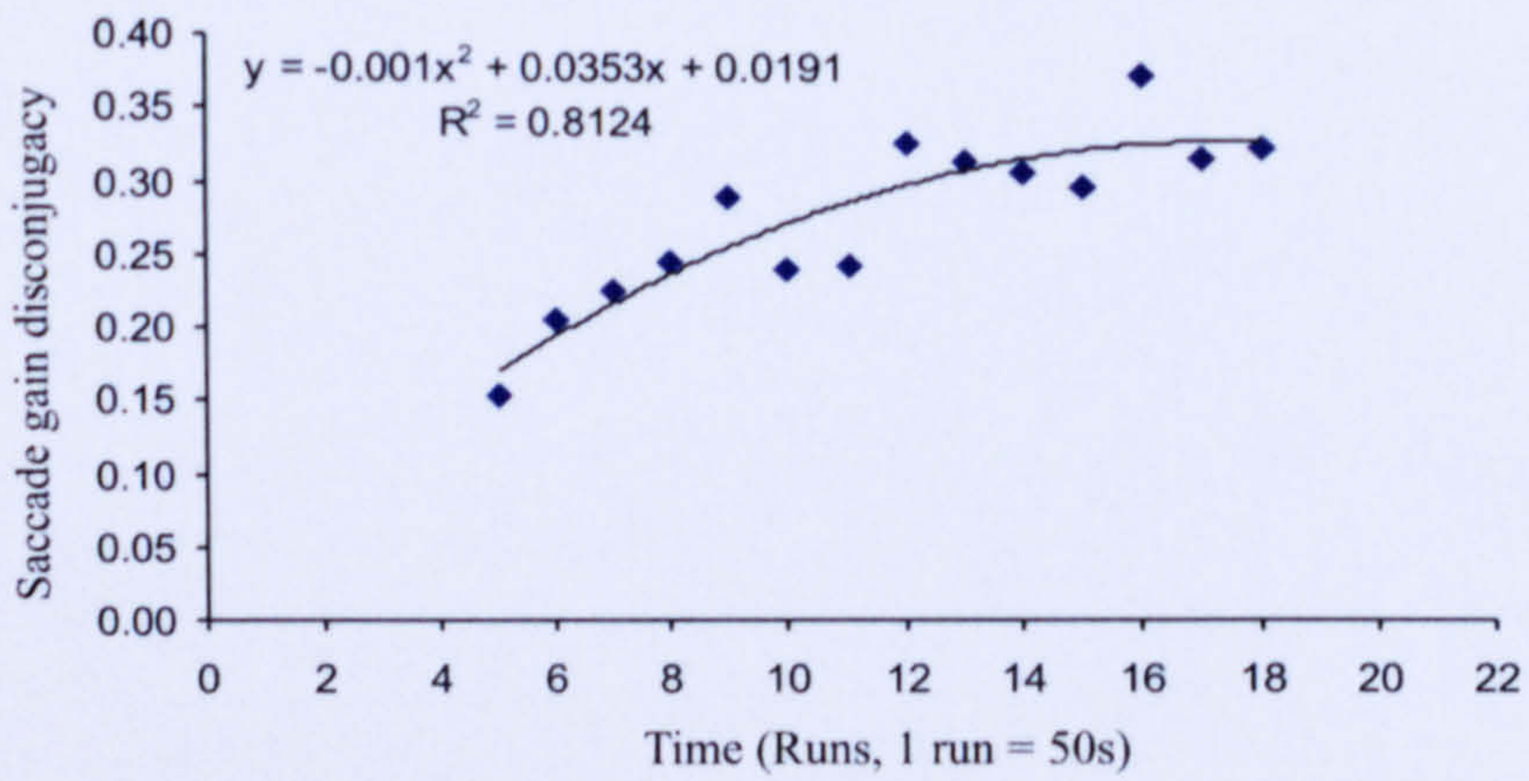
Figure A12.7: Mean saccade gain disconjugacy during the adaptation phase for BSV subjects (1, 2 & 4) and strabismic subjects (2, 4 & 9). Pooled data of four BSV subjects who received feedback to the dominant eye and three strabismic subjects who demonstrated appropriate disconjugate adaptation with feedback to the fixing eye. Polynomal curves fitted to the data.

Adaptation phase - feedback to non-dominant eye

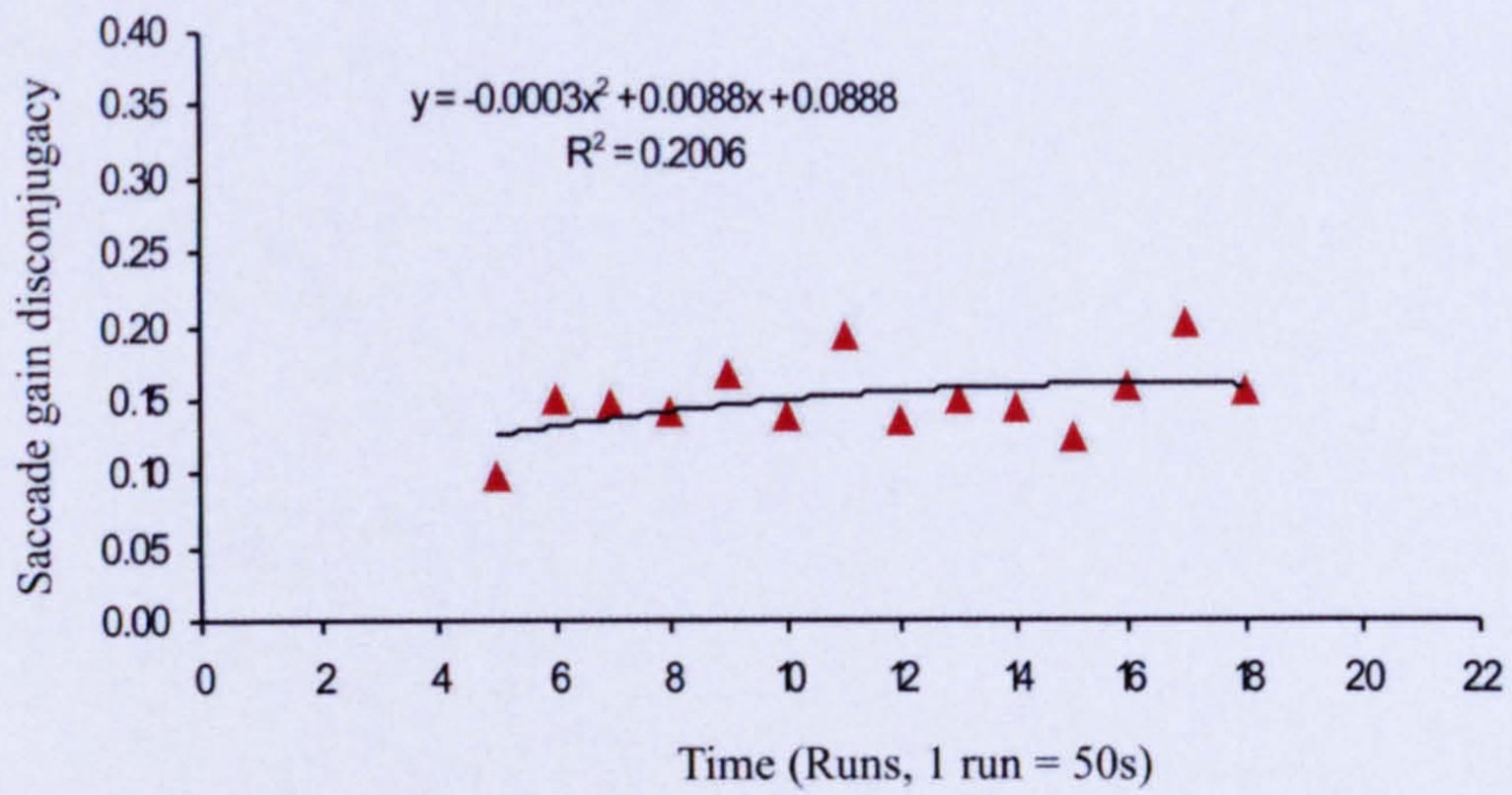
a) BSV subjects - convergent disparity



b) BSV subjects - divergent disparity



c) Strabismic subjects (appropriate adaptors) - convergent disparity



d) Strabismic subjects (appropriate adaptors) divergent disparity

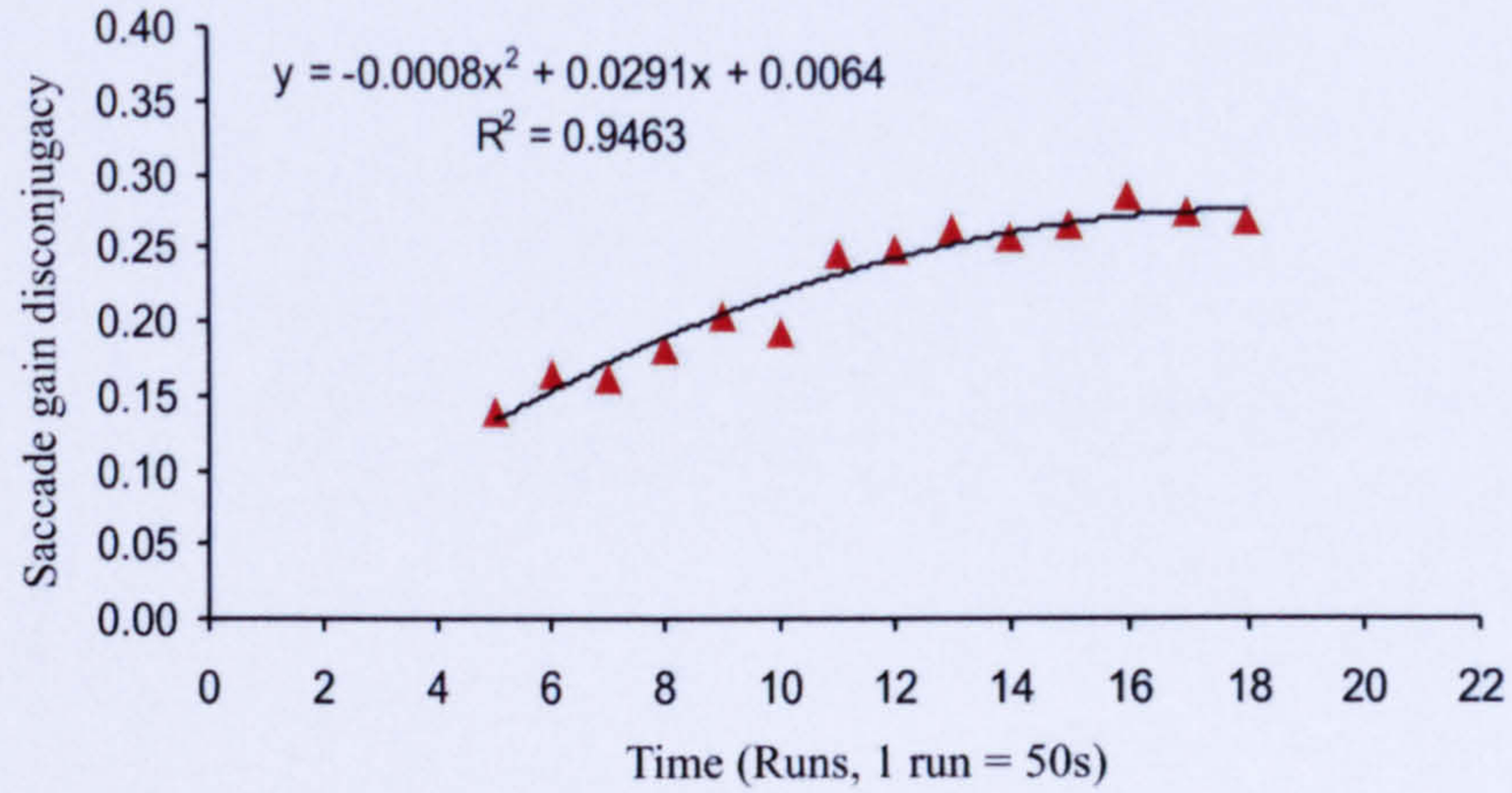


Figure A12.8: Mean saccade gain disconjugacy during the adaptation phase for BSV subjects (5, 6 & 8) and strabismic subjects (2, 4 & 6). Pooled data of four BSV subjects who received feedback to the non-dominant eye and three strabismic subjects who demonstrated appropriate disconjugate adaptation with feedback to the strabismic eye. Polynomal curves fitted to the data.

A12.4 Trend analyses for time course of adaptation

A12.4.1 Trend analyses – repeated measures

Factors: Time run 5 to 18
Disparity Convergent / divergent

Two-factor repeated measures trend analysis for three BSV subjects (1, 2, &4) with feedback to dominant eye
Linear

Source	SS	DF	MS	F	P
Trend	0.074	1	0.074	3.565	>0.05
TrendxS	0.041	2	0.021		
AxTrend	0.004	1	0.004	2.535	>0.05
AxTrendxS	0.003	2	0.002		

Quadratic

Source	SS	DF	MS	F	P
Trend	0.067	1	0.067	7.847	>0.05
TrendxS	0.017	2	0.008		
AxTrend	0.002	1	0.002	0.430	>0.05
AxTrendxS	0.008	2	0.004		

Cubic

Source	SS	DF	MS	F	P
Trend	0.000	1	0.000	0.037	>0.05
TrendxS	0.004	2	0.002		
AxTrend	0.002	1	0.002	0.820	>0.05
AxTrendxS	0.005	2	0.003		

Two-factor repeated measures trend analysis for three BSV subjects (5, 6, &8) with feedback to non-dominant eye
Linear

Source	SS	DF	MS	F	P
Trend	0.158	1	0.158	9.736	>0.05
TrendxS	0.033	2	0.016		
AxTrend	0.002	1	0.002	0.649	>0.05
AxTrendxS	0.008	2	0.004		

Quadratic

Source	SS	DF	MS	F	P
Trend	0.019	1	0.019	77.423	<0.001
TrendxS	0.000	2	0.000		
AxTrend	0.000	1	0.000	0.264	>0.05
AxTrendxS	0.000	2	0.000		

Cubic

Source	SS	DF	MS	F	P
Trend	0.001	1	0.001	0.387	>0.05
TrendxS	0.003	2	0.001		
AxTrend	0.001	1	0.001	1.673	>0.05
AxTrendxS	0.002	2	0.001		

Two-factor repeated measures trend analysis for three of strabismic subjects with feedback to the fixing eye (three subjects with appropriate direction adaptation = 2, 4 & 9).

Linear

Source	SS	DF	MS	F	P
Trend	0.154	1	0.154	27.297	<0.05
TrendxS	0.011	2	0.006		
AxTrend	0.001	1	0.001	0.131	>0.05
AxTrendxS	0.009	2	0.004		

Quadratic

Source	SS	DF	MS	F	P
Trend	0.010	1	0.010	17.523	<0.05
TrendxS	0.001	2	0.001		
AxTrend	0.005	1	0.005	4.691	>0.05
AxTrendxS	0.002	2	0.001		

Cubic

Source	SS	DF	MS	F	P
Trend	0.001	1	0.001	0.257	>0.05
TrendxS	0.011	2	0.006		
AxTrend	0.001	1	0.001	0.204	>0.05
AxTrendxS	0.007	2	0.003		

Two-factor repeated measures trend analysis for three strabismic subjects with feedback to the strabismic eye (three subjects with appropriate direction adaptation = 2, 4 & 6).

Linear

Source	SS	DF	MS	F	P
Trend	0.063	1	0.063	20.760	<0.05
TrendxS	0.006	2	0.003		
AxTrend	0.025	1	0.025	0.583	>0.05
AxTrendxS	0.084	2	0.042		

Quadratic

Source	SS	DF	MS	F	P
Trend	0.005	1	0.005	0.704	>0.05
TrendxS	0.014	2	0.007		
AxTrend	0.001	1	0.001	0.215	>0.05
AxTrendxS	0.011	2	0.005		

Cubic

Source	SS	DF	MS	F	P
Trend	0.000	1	0.000	0.053	>0.05
TrendxS	0.018	2	0.009		
AxTrend	0.006	1	0.006	2.544	>0.05
AxTrendxS	0.004	2	0.002		

A12.4.2 Trend analyses – mixed measures

Two-factor mixed measures trend analysis for convergent disparity with feedback to the dominant eye
Factors: Time run 5 to 18
Group BSV (3 subjects 1, 2 & 4) / strabismic (three subjects 2, 4 & 9)

Linear

Source	SS	DF	MS	F	P
Trend	0.119	6	0.020		
TrendxS	0.082	1	0.082	11.016	<0.05
AxTrend	0.007	1	0.007	0.881	>0.05
AxTrendxS	0.030	4	0.007		

Quadratic

Source	SS	DF	MS	F	P
Trend	0.027	6	0.005		
TrendxS	0.015	1	0.015	19.731	<0.01
AxTrend	0.009	1	0.009	11.321	>0.05
AxTrendxS	0.003	4	0.001		

Cubic

Source	SS	DF	MS	F	P
Trend	0.011	6	0.002		
TrendxS	0.001	1	0.001	0.233	>0.05
AxTrend	0.000	1	0.000	0.058	>0.05
AxTrendxS	0.011	4	0.003		

Two-factor mixed measures trend analysis for divergent disparity with feedback to the dominant eye
Factors: Time run 5 to 18
Group BSV (3 subjects 1, 2 & 4) / strabismic (three subjects 2, 4 & 9)

Linear

Source	SS	DF	MS	F	P
Trend	0.178	6	0.030		
TrendxS	0.142	1	0.142	16.345	<0.01
AxTrend	0.002	1	0.002	0.183	0.183
AxTrendxS	0.035	4	0.009		

Quadratic

Source	SS	DF	MS	F	P
Trend	0.084	6	0.014		
TrendxS	0.055	1	0.055	8.744	<0.05
AxTrend	0.004	1	0.004	0.688	>0.05
AxTrendxS	0.025	4	0.006		

Cubic

Source	SS	DF	MS	F	P
Trend	0.020	6	0.003		
TrendxS	0.000	1	0.000	0.005	>0.05
AxTrend	0.004	1	0.004	0.840	>0.05
AxTrendxS	0.017	4	0.004		

Two-factor mixed measures trend analysis for convergent disparity with feedback to the non-dominant eye Factors: Time run 5 to 18
Group BSV (three subjects 5, 6 & 8) / strabismic (three subjects 2, 4 & 6)

Linear

Source	SS	DF	MS	F	P
Trend	0.096	6	0.016		
TrendxS	0.049	1	0.049	6.349	<0.05
AxTrend	0.016	1	0.016	2.067	>0.05
AxTrendxS	0.031	4	0.008		

Quadratic

Source	SS	DF	MS	F	P
Trend	0.035	6	0.006		
TrendxS	0.008	1	0.008	1.286	>0.05
AxTrend	0.003	1	0.003	0.454	>0.05
AxTrendxS	0.024	4	0.006		

Cubic

Source	SS	DF	MS	F	P
Trend	0.013	6	0.002		
TrendxS	0.000	1	0.000	0.223	>0.05
AxTrend	0.006	1	0.006	3.862	>0.05
AxTrendxS	0.006	4	0.002		

Two-factor mixed measures trend analysis for divergent disparity with feedback to the non-dominant eye
Factors: Time run 5 to 18
Group BSV (three subjects 1, 2 & 4) / strabismic (three subjects 2, 4 & 9)

Linear

Source	SS	DF	MS	F	P
Trend	0.284	6	0.047		
TrendxS	0.183	1	0.183	7.355	<0.05
AxTrend	0.000	1	0.000	0.015	>0.05
AxTrendxS	0.100	4	0.025		

Quadratic

Source	SS	DF	MS	F	P
Trend	0.015	6	0.002		
TrendxS	0.014	1	0.014	99.734	<0.001
AxTrend	0.000	1	0.000	1.557	>0.05
AxTrendxS	0.001	4	0.000		

Cubic

Source	SS	DF	MS	F	P
Trend	0.022	6	0.004		
TrendxS	0.000	1	0.000	0.075	0.075
AxTrend	0.001	1	0.001	0.224	0.224
AxTrendxS	0.021	4	0.005		

12.5 Three-factor mixed measures ANOVA for time course of adaptation

Feedback dominant eye
To test for differences between the adaptation phase of the three subjects in BSV group (1, 2 & 4) and three strabismic subjects who adapted in an appropriate direction (2, 4 & 9).

Factors

1. Group	BSV / Strabismic	g
2. Disparity	Convergent / divergent	d
3. Time	run 5 to run 18	t

	DF	SS	MS	F	P	Lambda	Power
g	1	0.032	0.032	1.297	0.3183	1.297	0.141
Error	4	0.098	0.024				
d	1	0.006	0.006	0.099	0.7690	0.099	0.057
gd	1	2.616E-6	2.616E-6	4.191E-5	0.9951	4.191E-5	0.050
Error	4	0.250	0.062				
t	13	0.296	0.023	6.384	<0.0001	82.995	1.000
gt	13	0.054	0.004	1.157	0.3365	15.039	0.596
Error	52	0.186	0.004				
dt	13	0.019	0.001	0.825	0.6325	10.722	0.425
gdt	13	0.039	0.003	1.694	0.0903	22.019	0.806
Error	52	0.093	0.002				

Feedback non-dominant eye
To test for differences between the adaptation phase of the three subjects in BSV group (5, 6 & 8) and three strabismic subjects who adapted in an appropriate direction (2, 4 & 6).

Factors

1. Group	BSV / Strabismic	g
2. Disparity	Convergent / divergent	d
3. Time	run 5 to run 18	t

	DF	SS	MS	F	P	Lambda	Power
g	1	0.192	0.192	1.600	0.2746	1.600	0.162
Error	4	0.480	0.120				
d	1	0.139	0.139	4.982	0.0894	4.982	0.397
gd	1	0.012	0.012	0.426	0.5494	0.426	0.080
Error	4	0.112	0.028				
t	13	0.253	0.019	6.778	<0.0001	88.110	1.000
gt	13	0.037	0.003	0.990	0.4738	12.871	0.513
Error	52	0.149	0.003				
dt	13	0.029	0.002	0.682	0.7712	8.867	0.348
gdt	13	0.021	0.002	0.488	0.9215	6.346	0.246
Error	52	0.169	0.003				