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The effect of distractors on saccades and adaptation of saccades in strabismus

Helen Griffiths PhD, DBO[1], Jon Whittle PhD [2], David Buckley PhD[1]

1. Academic Unit of Ophthalmology & Orthoptics, University of Sheffield, UK

2. Sheffield Teaching Hospital Trust, Royal Hallamshire Hospital, Sheffield, UK

Corresponding Author

Dr Helen Griffiths
Lecturer in Orthoptics
Academic Unit of Ophthalmology & Orthoptics
Floor K, K.125a
University of Sheffield
School of Medicine & Biomedical Sciences
Beech Hill Road
Sheffield S10 2RX

Telephone: (0114) 271 2713
Fax: (0114) 271 3314
Email: h.griffiths@sheffield.ac.uk

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Abstract

This paper reports two experiments to determine the contribution of the suppressing eye to the generation of saccadic eye movements in constant strabismus. Eye movements were recorded using a Skalar infra-red recorder. Experiment 1 tested 6 participants with constant strabismus, pathological suppression and no clinically demonstrable binocular single vision (BSV). We explored the effect of visual distractors presented monocularly (to either the fixing eye or the

strabismic eye) and binocularly, on saccade latency and accuracy. Saccade latency significantly increased when distractors were presented to the strabismic eye compared to the no distractor condition. In all participants the effect on latency, with distractors presented to the strabismic eye, was maximum when distractors were presented towards the location of the anatomical fovea. Saccade accuracy was reduced with ipsilateral distractors to the target when presented binocularly or monocularly to the fixing eye but not affected by distractors presented to the strabismic eye. Experiment 2 investigated fast disconjugate saccade adaptations in 6 participants with constant strabismus, pathological suppression and no clinically demonstrable binocular single vision (BSV) and for comparison 8 with normal bifoveal BSV. An electronic feedback system in which the calibrated eye movement position signal could be scaled by a factor (the feedback gain) to move the target visible to one eye during binocular viewing was used to induce saccade disconjugacy. In all BSV participants and 3 of 6 participants with constant strabismus, saccadic adaptation occurred rapidly such that under conditions of visual feedback saccades became increasingly disconjugate. These disconjugacies persisted when normal viewing conditions were restored. The presence of an adaptive mechanism to adjust the binocular co-ordination of saccades in the presence of constant strabismus with suppression and no clinically demonstrable BSV has been demonstrated. Mechanisms that might explain such results are discussed.

Keywords: distractor, strabismus, suppression, monocular, binocular, saccade

Introduction

In the presence of manifest strabismus with onset in childhood the deviating eye is typically suppressed with patients unaware of objects stimulating areas within the suppression area to avoid symptoms of diplopia and confusion. The mechanism of suppression in strabismus is unclear and the contribution of the strabismic eye, when suppressed, to visual performance and to the generation of eye movements has received little attention. Immediately post-operatively patients may be disorientated following correction of strabismus despite lack of diplopia and no potential for fusion. This may suggest therefore that sub-consciously images from the deviating eye are contributing to visual processing and eye movement programming.

Studies of saccades in the presence of concomitant strabismus (strabismus in which the angle of deviation remains the same in all directions of gaze, which ever eye is fixing) are not abundant, for review see Griffiths (2007), but are of interest in that analysis of saccade characteristics provides

information about cortical function and information about the link between binocular vision and binocular coordination of saccades.

Most previous studies which have documented eye movements in concomitant strabismus have concluded that saccade characteristics, such as latency and gain, are in general unaffected by the presence of concomitant strabismus in the absence of amblyopia (Ciuffreda et al, 1978; de Faber et al, 1994; Kapoula & Bucci, 2002; Griffiths, 2004; Bucci et al 2006). The literature also documents no significant change to saccade performance following surgical intervention to the extraocular muscles (Kapoula & Bucci, 2002) despite evidence of altered velocity profiles (Chen et al 2005). The main effect on saccades in concomitant strabismus is disconjugacy, which is significantly increased (Kapoula et al 1997) but significantly reduces following surgically improved alignment despite lack of binocular vision suggesting that fusion is not required for adaptations to binocular coordination of saccades.

In normal binocular single vision (BSV), distractors briefly presented simultaneously with a target have been shown to increase saccade latency and decrease saccade accuracy (Walker et al, 1997). An earlier study (Griffiths, Whittle & Buckley, 2006) examined the effect of distractors presented binocularly and monocularly (to the dominant eye and non-dominant eye) in participants with BSV. This concluded that saccade latency was increased significantly when distractors were presented binocularly compared to monocular presentation to the dominant or non-dominant eye. Experiment 1 explored the effect of distractors presented monocularly and binocularly in participants with strabismus and the sensory adaptation of pathological suppression. 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. If the strabismic eye contributes to saccadic eye movement planning, distractors presented to the strabismic eye only should alter saccade latency and/ or saccade gain compared to the no distractor condition. To our knowledge this has not been tested nor has the work reported in our Experiment 2. Here we tested the involvement of the strabismic eye in fast disconjugate adaptation; the relevant literature is reviewed after Experiment 1.

Experiment 1

Methods

Participants

Prior to recruitment of volunteers ethical approval was obtained for both experiments. Six participants (mean age 34.3 ±17.0) with constant strabismus, normal retinal correspondence, no potential BSV and suppression were studied; three with esotropia and three with exotropia. A clinical assessment of their visual function and strabismus was performed and details of this are shown in Table 1.

Apparatus

Eye movements were recorded using an IRIS 6500 infrared limbal tracker, (Skalar Medical, Delft, The Netherlands). The analogue output was filtered through a 100 Hz low-pass filter, digitised to 12-bit resolution and sampled at 5 ms intervals. Head movements were restricted by use of a chin and cheek rest, for schematic diagram of laboratory set-up see Figure 1 of Griffiths et al (2006). The eye movement recordings were stored on disk and analysed off-line.

A 1° cross target was presented by back projection in the centre of a translucent screen 114cm from the participant. A mirror galvanometer sited in front of the projector was used to reposition the target randomly at either 4° or 8° eccentricities along the horizontal axis. The target was always presented to both eyes.

A second projector with mirror galvanometer was used to back project a distractor onto the screen. The distractor consisted of an unfilled circle, diameter 1.5° which (when presented) appeared for 200ms simultaneously with the onset of the target.

The target size, distractor size and distractor duration were selected following a pilot study run on two participants with normal binocular vision. Those selected gave a distractor effect comparable with Walker et al (1997). The target and distractors were larger than Walker et al (1997) but were considered to be of an appropriate size to allow visibility by participants with mild to moderate amblyopia and were identical in size and luminance to those used in our previous study of participants with normal BSV (Griffiths et al, 2006). The 4° and 8° target amplitudes and distractor positions were as shown in Figure 1 and were selected to be comparable to the experiments of Walker et al (1997).

********** FIGURE 1 ABOUT HERE **********

In the experiment three distractor conditions were used; distractor to both eyes simultaneously, to the dominant eye only, to the non-dominant eye only. Distractor presentation to one or both eyes was controlled by 4 liquid crystal polymer (LCP) shutters (Phillips Components), one positioned between the lens and the mirror galvanometer of each projector and one positioned in front of each of the participants eyes. All 4 shutters were run at a frequency of 80Hz. Alteration of the relative timings of the shutters allowed presentation of the distractor to one eye or both eyes. A series of experiments confirmed that the shutters did not allow any crosstalk between the eyes (Griffiths, 2004). A stationary background comprised of fine random dots of luminance 2cd/m^2 was back projected by a third slide projector and was visible to both eyes at all times. Room illumination was kept constant throughout the experiment at 1cd/m^2.

Procedure

A clinical examination was initially performed to classify the type of strabismus, confirm that this was a constant strabismus present at all distances, and to investigate the presence, area and density of suppression. Within one week of the clinical assessment the participants attended three separate eye movement-recording sessions within a period of ten days.

For eye movement recording the participant was seated with the Skalar infrared eye movement recorder and LCP shutters in place. Before each block of 20 trials the participant was informed or reminded 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 correct target direction. Participants were instructed to look directly at the centre of the small 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 look 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. They were told that occasionally a circle (i.e. the distractor) could appear anywhere on the screen, but this should be ignored at all times.

Eye movements generated using a sinusoidal target motion of 0.32Hz, ±12°, were used to calibrate the eye movement recorder before each block of 20 trials. Participants were asked to follow the centre of the target as accurately and smoothly as possible.

The target was initially presented centrally. 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 (0 gap). The target then returned to the centre point before the next presentation. In most trials a distractor appeared simultaneously with the onset of the 4 or 8° target for 200ms. The eccentricity of the distractor varied randomly between ±10° at 2° intervals along the horizontal axis, where positive values represent distractors ipsilateral to the target and negative values represent distractors on the contralateral side to the target. Zero indicates distractors presented at the original fixation point. In 60 out of 720 trials, one per block, no distractor was presented. The mean data from this condition provided baseline measures. A total of 12 blocks of trials, each consisting of 20 saccades, was run for each distractor condition (distractor to both eyes, dominant eye and non-dominant eye) in a random order, giving 20 saccades at each distractor eccentricity, 240 saccades for each distractor condition and a total of 720 saccades. The experiment was carried out over three testing sessions each of 45 minutes completed within a ten-day period.

The angle of strabismus 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 1º target cross, back projected on to the screen at a distance of 114cm, and the participants 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.

Results

All six participants with constant strabismus and suppression completed the experiment and were included in the analysis. All had 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 further experiment showed that whilst fixating the central fixation target presented to both eyes, all participants 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 Appendix for results).

Saccades were detected using an acceleration criterion, which defined the start of a saccade as occurring when eye acceleration exceeded twice the noise level. Each saccade was then checked visually to confirm correct detection of the primary saccade. Mean saccade latency and gain for

each individual participant 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 participants a small number of saccades could not be analysed due to blinks or incorrect fixation. A total of 12% 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 and saccade gain. In each of these sections the mean response of the group are firstly presented, followed by individual participant responses.

Saccade latency

The mean saccade latency for target presentations without distractors for each of the six participants was 161.4 ±16.7ms for 4º targets and 167.44 ±11.6ms for 8º targets. Figure 2 shows the group 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.

Figure 2 shows that all participants demonstrated a similar response with distractors presented to both eyes and to the dominant eye. For both 4º and 8º 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; for 4º targets latency is increased with contralateral distractors between -4º and -10º, at the original fixation point and very slightly for ipsilateral distractors at +10º. The mean increase for the group was small and similar in these positions, being approximately 10ms. For 8º targets latency increased for contralateral distractors between -2º and -6º. Similarly to 4º targets the increase was small with the maximum increase of almost 13ms with distractors at -4º.

********** FIGURE 2 ABOUT HERE **********

Distractor at fixation

The largest increase in latency for both eyes and fixing eye distractor conditions occurred at the original fixation point, represented as zero. For 4º 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 8º 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.

From Figure 2 it can be seen that when the distractor is presented to the strabismic eye, effects on latency are present for 4º but less than the other two conditions. The increase at fixation for 4º targets was 10.5ms and 8º targets 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). 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 2 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).

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 [$F(1,5)=3.586$, $P>0.05$].

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°). 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 significantly 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 2 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.

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 2 this appears to have resulted from the increased effect on latency for contralateral distractors between -2° and -6°.

Individual data

With distractors presented to the strabismic eye the lack of a clear peak latency increase in Figure 2 may have been masked as the participants had different angles of strabismus. Individual data was therefore plotted and is shown in Figures 3 and 4 for 4° and 8° targets respectively.

********** FIGURE 3 and 4 ABOUT HERE **********

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 these maximum increases and location is shown in Table 2. Participants 1 and 2 showed an increased effect with binocular presentation compared with distractors to the fixing eye only. This difference is small for participant 1 (8.6ms for 4 degree targets) but large for participant 2 (22ms for 4 degree targets). This is reversed for Participants 4 and 5 who both showed a larger effect with distractors

to the fixing eye only compared with the binocular stimulation. The remaining two participants had equal effects for fixing eye and binocular distractor presentations.

Saccade Gain

The mean saccade gain for target presentations without distractors was 1.011±0.119 for 4º targets and 0.883±0.049 for 8º targets. Figure 5 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.

********** FIGURE 5 ABOUT HERE **********

All participants demonstrated a typical distractor effect with distractors to both eyes and fixing eye. For 4º targets a clear decrease in gain occurred for ipsilateral distractors at +2º and an increase in gain occurred with distractors beyond the target from +6º to +10º when distractors were presented to both eyes and fixing eye only. The largest increase in gain for both conditions occurred with distractors at +10º. 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 8º targets a large decrease in gain occurred for ipsilateral distractors presented between the original fixation point and the target (+2º to +6º) 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 participants showed small alterations to saccade gain when distractors were presented to the strabismic eye. From Figure 5 it can be seen that, when the distractor was presented to the strabismic eye, effects on gain were small for 4º targets. The maximum increase in gain occurred at +8º where an increase in gain of 0.187 was present. There was a minimal effect at +4º for 8º targets.

Gain for distractors contralateral and ipsilateral to the target

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°). 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 5 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. 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. 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.

Individual data

To identify any individual patterns individual participant data was examined. Participants 4 and 5 showed no effect on saccade gain with distractors presented to the strabismic eye. Participant 3 demonstrated a normal effect for ipsilateral distractors but also increased gain for contralateral distractors. For 4º targets participants 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°. Participant 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 small with two participants having no effect. Two of the six participants demonstrated larger effects on gain with distractors presented to both eyes compared to distractors presented to the fixing eye only.

Discussion of Experiment 1

In strabismic observers with suppression the maximum effect on latency, with distractors to the fixing eye and both eyes, was equivalent in magnitude and location to that previously reported in the observers with normal BSV (Griffiths, et al 2006). Whilst the maximum effect produced from the strabismic eye (distractors at the anatomical fovea) was approximately one third of the size. When individual participant data were examined the maximum effect produced from the strabismic eye appeared to occur when distractors were presented in the area of the anatomical fovea.

The effects on saccade accuracy from distractors to the strabismic eye in observers with suppression were small with two observers having no response at all. The enhanced effect of binocular distractors, previously demonstrated in normal BSV (Griffiths et al, 2006), was not present in the strabismic participants possibly as the dominant eye had an increased effect. Distractors in the strabismic eye had a variable effect on gain between participants. 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 5). 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 4º targets. Distractors presented within the suppression area of the strabismic eye did therefore affect gain.

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 and Jürgens, 1979). However Olivier, Dorris and Munoz, (1999) suggest, following recording of neuronal activity in the monkey, that both effects can 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.

Mechanism for the distractor effect in suppression

In strabismic participants with suppression the maximum effect on latency, with distractors to the fixing eye and both eyes, was equivalent or greater in magnitude to that previously reported 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 participants with suppression were small with two participants having no response at all.

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 (Sengpiel, Blakemore, Kind & Harrad, 1994). The presence of a distractor effect from the strabismic eye during suppression in our findings 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 are the variable effects explained? Variability in the response was found; with different effects occurring for 4º and 8º 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. 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 may be occurring in strabismic participants that determine awareness of visual stimuli whilst an extrastriate cortical route allows visual information to be used for saccade programming.

It is possible that a high sensitivity exists in suppression for detection of transient onset and offset of a target. This has been described in a patient 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. Wolfe (1986) demonstrated that, in six participants 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.

The strabismic participants in this present study all had relatively small angles of deviation, maximum 18Δ. It would therefore be interesting to extend this study 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 saccadic programming. It may be that the effect diminishes as the angle increases due to either retinal changes towards the periphery or the anatomical fovea becoming too remote from the target to influence the saccade.

Experiment 2

In Experiment 1 we found that presentation of distractors to the strabismic eye had a small effect on saccade characteristics, in Experiment 2 we test for any involvement of the strabismic eye in fast disconjugate saccadic adaptation.

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

Experiments in symmetric saccadic adaptive control have been carried out using techniques such as intra-saccadic step (Deubel, Wolf and Hauske 1986) and electronic feedback systems (Albano and King 1989).

Saccades may also adapt 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 spectacle lenses resulted in visual images that were differently sized for the two eyes. Disconjugate saccades occurred with induced anisometropia ranging from 2D to 8D, with the adaptations almost complete within one hour. Later studies (Kapoula, Eggert and Bucci 1995; Van der Steen and Bruno 1995) show that, under similar conditions where the image to one eye is magnified, disconjugacy occurs within a period of a few minutes and that it persists under monocular viewing. This indicates the presence of a fast learning mechanism.

As disconjugate adaptation sub-serves binocular vision, Kapoula, Bucci, Eggert and Zamfirescu (1996) questioned whether foveal fusion is a prerequisite to achieve disconjugate adaptations. They studied three micro-strabismic participants who viewed a random dot pattern, which was

10% larger in one eye. 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 demonstrates that foveal fusion is not required for this mechanism and peripheral fusion is sufficient to drive adaptive changes.

Bucci, Kapoula, Eggert and Garraud (1997) examined the degree of binocular vision necessary to stimulate disconjugate adaptation. They studied two participants with small esotropia and peripheral fusion, two with intermediate esotropia, ARC and anomalous BSV and four participants with large esotropia and no demonstrable binocular vision. The conclusions were that participants 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, participants without binocular vision made disconjugate changes to the amplitude of saccades, but these were not in the direction appropriate for the induced disparity. The authors therefore concluded that binocular vision (normal or anomalous) is required to stimulate the appropriate mechanism of saccade adaptation.

In the experiment outlined above, all participants with strabismus and no potential BSV had their angle of deviation corrected, or partially corrected, with base out prisms, ranging from 2 to 22Δ, placed over the deviating eye. The reason stated for this was to render disparities similar in all participants. This may however 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 would have been detected and hence an appropriate disconjugate adaptation of saccades could be triggered.

Experiment 2 investigates disconjugate saccade adaptation in normal BSV and in strabismus with no demonstrable binocular vision without correction of the angle of strabismus. The method used to induce retinal disparity of targets was an electronic feedback system.

Methods

Participants

Fourteen adult participants were included in this experiment, eight with normal bifoveal BSV (mean age 29.3 ±9.6) and six with manifest strabismus (mean age 33.5 ±15.9). The group with

normal BSV were all right eye dominant and had corrected visual acuity of at least 6/6 Snellen and no ocular motility defects. The participants with strabismus all had constant suppression and no clinically demonstrable BSV, their details are summarised in Table 1. Four of the strabismic participants took part in Experiment 1 (participants 3 to 6).

Apparatus

The participants were seated comfortably 114cm from a flat back projection screen. The participant's head was stabilised using a chin and cheek rest, ensuring close fitting of cheek rests against the cheek bones and instructing the participant to remain firmly in position.
For details of the apparatus see Figure 1 of Griffiths et al (2006). Two modified Kodak carousel slide projectors projected identical sized targets. The targets consisted of a cross, subtending 2° of 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. Four liquid crystal polymer (LCP) shutters, one positioned in front of each projector lens and one in front of each eye and all operating at 80Hz, were set such that one target was visible to each eye. A blurred random dot stationary background of luminance 4 cd/m^2 was back projected by a third projector, and was constantly visible to both eyes.

Horizontal eye movements were recorded using a Skalar IRIS 6500 infrared limbal tracker. 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, could be instantaneously adjusted between -1 and +1 in 0.05 steps. Zero feedback gain represented normal viewing conditions. When the feedback gain was >0 the target moved in the same direction as the eye; at +1 the target moved at the same speed as the eye. If feedback gain was <0, the target moved in the opposite direction to the eye (not used in this experiment). Feedback could be applied to one of the targets, visible to one eye only, to induce saccade disconjugacy.

Procedure

Each eye movement recording 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. The pre and post-adaptation phases were the same in all phases 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. 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 eight participants with normal BSV attended two sessions: one session where the feedback condition was performed and another for the control condition. All participants were right eye dominant, four had feedback applied to the dominant eye and four had feedback applied to the non-dominant eye. The six participants 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 counterbalanced.

Participants 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. The participant was informed of the gaze direction prior to commencing the experiment. Each experimental session lasted approximately 30 minutes. Calibration of eye movements was performed prior to each phase.

The two identical overlapping targets, one visible to each eye, appeared in the centre of the screen and, after a randomised time delay (500 to 1500ms), jumped 5° to the right or left of centre. Following a randomised period (500 to 1500ms) the targets would both return to the centre. In the feedback condition adaptation phase, both targets would jump from the centre to 5° eccentricity, when the eye with feedback moved to fixate the target, the dissociated target visible to that eye 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. Convergent disparity occurred where the adducting eye was required to make a larger saccade than the abducting eye and divergent disparity when the abducting eye was required to make larger saccades than the adducting eye.

The pre- and post-adaptation phases were performed with monocular fixation by closing the LCP shutter in front of the non-dominant or non-preferred eye. The adaptation phase was performed with LCP shutters to both eyes open.

Results

The mean gain of saccades in each eye was calculated, the gain of the eye without feedback was subtracted from the eye with feedback to determine the saccade gain disconjugacy in the pre- and post-adaptation phases. Saccade gain disconjugacy in the pre-adaptation phases was subtracted from the post-adaptation saccade gain disconjugacy to give the magnitude of the adaptation effect. When no feedback was applied during the adaptation phase there was no significant change in disconjugacy of saccades between the pre and post-adaptation phases in any of the participants, paired t-tests $p>0.05$. The feedback, applied during the adaptation phase, induced appropriate saccade disconjugacy in all eight participants with normal BSV. The results for all BSV participants were pooled and the mean and range of their results are shown in Figure 6 as solid and dotted lines respectively. In the strabismic group examination of individual participant data reveals variable results; this is shown in Figure 6. Five of the six participants demonstrated adaptive changes to saccade disconjugacy following the adaptation phase when feedback was applied to a target visible to one eye.

********** FIGURE 6 ABOUT HERE **********

Three participants (participants 3, 4 and 8) 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 participant 8 although appropriate in direction, was significantly larger than the binocular participants when feedback was introduced to the strabismic eye ($p<0.01$). Participant 7 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. Participant 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. Participant 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 participant occurred for convergent disparity when feedback was applied to the strabismic eye, the adaptation effect was small and inappropriate to the induced disparity. This participant 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. 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 participant had variable amounts of disconjugacy under all test conditions and had no clear adaptation effect.

To determine whether the changes in disconjugacy for each participant were significantly different from the binocular participants, 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 participant to obtain a z score. Z scores were then converted to probability (using the table of normal distribution) of the participant being different from the BSV group. If adaptation occurred in the strabismic participant the p value would be non-significant. A summary of these results is shown in Table 3.

Time course of saccade adaptation

To identify any differences in the response between the participants with normal BSV and participants with strabismus the adaptation phase was examined further. Figure 7 and 8 show the mean saccade gain disconjugacy over the time course of the three experimental phases, with feedback applied to the dominant (Figure 7) and non-dominant eye (Figure 8). The figures are pooled data of three BSV participants, who demonstrated similar adaptation patterns and three strabismic participants (3,4 and 8) who adapted in the appropriate direction for the induced disparity. The mean disconjugacy and standard error for each run (15 saccades) is plotted.

********** FIGURE 7 & 8 ABOUT HERE **********

From Figures 7 and 8 the time course of adaptation appeared similar in all participants within each group. A small amount of disconjugacy was present in the pre-adaptation phase, which was fairly consistent for the four runs in this phase. The largest increase in disconjugacy occurred in participants 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 participants. A similar effect was seen in the strabismic participants. In both groups of participants 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.

Eight 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 and 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. 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 7a was not significantly different from Figure 7b and Figure 7c was not significantly different from Figure 7d. Also there were no significant differences between the time course of adaptation for BSV participants and strabismic participants, such that for example, the data shown in Figure 8a was not significantly different from Figure 8c and Figure 8b was not significantly different from Figure 8d.

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 $F(13,52)=6.778$, $p>0.0001$].

The results show that both groups of participants essentially have the same time course of adaptation, as demonstrated in Figures 7 and 8 and supported statistically.

Discussion of Experiment 2

The electronic feedback system applied to a target visible to one eye produced rapid disconjugate saccade adaptation in eight participants with normal bifoveal BSV. The aim of this study was to determine whether participants with manifest strabismus and no demonstrable fusion, normal or anomalous, could produce disconjugate saccades under such test conditions. The results demonstrate that three of six strabismic participants studied were able to produce appropriate disconjugate adaptations despite no clinically detectable binocular co-operation. The three participants who adapted in the appropriate direction had small angled deviations (8Δ esotropia, 8Δ exotropia and 12Δ exotropia) could therefore be considered likely candidates for development of abnormal retinal correspondence and anomalous binocular vision. Extreme care was taken clinically to investigate the participants with detailed questioning for binocular tests requiring

subjective responses and a complete investigation, with a full range of tests employed. Bucci et al (1997) have demonstrated disconjugate adaptations in intermediate strabismus with abnormal binocular vision. They describe such adaptations in two participants 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 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 participants. Participant 6 adapted in the appropriate direction (although by a larger amount than the normal BSV group) despite having the lowest VA of the group (0.6 logMAR). The age of onset of strabismus appeared to have been a significant factor as participant 7, who demonstrated constant anomalous adaptation responses, and participant 4, who had no response, had onset of strabismus before six months of age. The other four participants who showed adaptation all had onset of strabismus reported as ≥ 1year of age.

The maximum angle of deviation in which an appropriate adaptation response was found was 12Δ (one participant with esotropia of 12Δ and one participant with exotropia of 12Δ). Of the two participants with strabismus measuring 18Δ, one had no response at all and the other had a variable response. This finding is compatible with the results of Bucci et al (1997) who failed to find normal saccadic adaptation in 4 participants with no demonstrable fusion and esotropia of between 14 and 30Δ. The differences between the present study and Bucci et al (1997) were the method of inducing disconjugacy and the participants reported by Bucci et al (1997) were corrected with prisms either fully or partially, to present the disparities close to the fovea of the deviating eye. The participants reported in this current study, did not have the strabismus corrected, to determine how they would respond when in their 'normal' sensory state. It was shown that the two participants with angles of deviation >12Δ did not demonstrate normal saccade adaptation with their 'normal' strabismic angle.

The mechanism for the resulting difference in primary saccade amplitude in each eye in BSV would appear to be due to re-scaling of the pulse step signal based on the post-saccadic disparity, with the primary aim of maintaining BSV. A mechanism in the strabismic participants who adapted normally or abnormally is less clear.

In the absence of fusion there could be a purpose in ensuring that the retinal image stimulating the deviating eye is maintained in a reasonably constant position, this might be to ensure that it remains within the suppression area and to avoid diplopia. If no adaptation or in appropriate 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. The pathway to drive such a response is also unclear. It is possible that despite a lack of cortical perception of suppressed images that information from the strabismic eye sub-cortically allows adaptation of saccades to avoid diplopia.

Bucci et al (1997) proposed that the anomalous disconjugacy (inappropriate for induced disparity) seen in participants 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 (1991). This is a primitive form of binocular vision found in vertebrates with complete decussation of the visual pathways. Bucci et al (1997) suggested that this form of independent eye control could allow avoidance of diplopia but not establishment of a true binocular linkage.

Final Discussion

In strabismus, with suppression, increased saccade latency occurred when distractors were presented to the strabismic eye compared to the no distractor condition. In all participants the effect on latency, with distractors presented to the strabismic eye, was maximum when distractors were presented towards the location of the anatomical fovea.

Saccade accuracy was only minimally affected by distractors presented to the strabismic eye in 4 of the 6 observers with suppression. No increased effect occurred with binocular distractor presentations compared to monocular presentation in strabismic participants 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 participant.

Experiment 2 demonstrated that binocular vision is not required for disconjugate saccade adaptation. Five of the six participants demonstrated disconjugate changes. Three participants with manifest strabismus, no potential normal BSV or clinically demonstrable anomalous BSV and angles of deviation up to 12Δ, (1 esotropia, 2 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 participants with normal BSV. A mechanism for such results has been discussed but remains unclear. Two participants demonstrated adaptations in a direction inappropriate for the disparity.

References

Albano JE, King WM. Rapid adaptation of saccadic amplitude in humans and monkeys. Investigative Ophthalmology and Visual Science 1989, 30: 1883-1893.

Barbur JL, Forsyth PM, Findlay JM. Human saccadic eye movements in the absence of the geniculocalcarine projection. Brain 1988, 111:63-82.

Becker W, Jürgens R. An analysis of the saccadic system by means of double step stimuli. Vision Research 1979, 19:967-983.

Bucci MP, Kapoula Z, Eggert T, Garraud L. Deficiency of adaptive control of the binocular co-ordination of saccades in strabismus. Vision Research 1997, 37:2767-2777.

Bucci MP, Kapoula Z, Yang Q, Bremond-Gignac D. Latency of saccades, vergence, and combined movements in children with early onset convergent or divergent strabismus. Vision Research 2006; 46: 1384-1392.

Bucci MP, Kapoula Z, Yang Q, Roussat B, Brémond-Gignac D. Binocular coordination of saccades in children with strabismus before and after surgery. Investigative Ophthalmology & Visual Science 2002; 43: 1040-1047.

Braddick O, Atkinson J, Hood B, Harkness W, Jackson G, Vargha-Khadem F. (1992). Possible blindsight in infants lacking one cerebral hemisphere. Nature, 360:461-463.

Bronstein AM, Kennard C. Predictive eye saccades are different from visually triggered saccades. Vision Research 1987, 27:517-520.

Chen SI, Knox PC, Hiscott P, Marsh IB. Detection of the slipped extraocular muscle after strabismus surgery. Ophthalmology 2005; 112: 686-693.

Ciuffreda KJ, Kenyon RV, Stark L. Processing delays in amblyopic eyes: evidence from saccadic latencies. Am J Optom Physiol Opt. 1978; 55: 187-196.

Collewijn H, Erkelens CJ, Steinman RM. Binocular co-ordination of human horizontal saccadic eye movements. Journal of Physiology (London) 1988, 404:157-182.

de Faber JTHN, van Rijn LJ, Collewijn H. Dynamics of saccades in strabismus and amblyopia.; In H. Kauffmann (ed.) Transactions of the 21st European Strabismological Association 1994, 303-308.

Deubel H, Wolf W, Hauske G. Adaptive gain control of saccadic eye movements. Human Neurobiology 1986, 5:245-253.

Findlay JM. Visual information for saccadic eye movements. In Hein A, Jeannerod M. (Eds). Spatially oriented behaviour. New York: Springer-Verlag, 1983, pp281-303.

Fischer B, Weber H. Express saccades and visual attention. Behavioural Brain Research 1993, 16:553-610.

Goldberg ME, Robinson DL. Visual systems: superior colliculus. In Masterson RB. (Ed.). Handbook of behavioural Neurology: Sensory integration. New York: Plenum Press 1978.

Griffiths HJ. Saccades in Strabismus: A Literature Review. Br. Irish Orthopt. J. 2007;4, 3-8.

Griffiths HJ. Saccades in the absence of binocular vision. PhD Thesis, University of Sheffield, 2004:79-98.

Griffiths HJ, Whittle J, Buckley D. The effect of binocular and monocular distractors on saccades in participants with normal binocular single vision. Vision Research. 2006;46:72-81.

Holliday IE, Anderson SJ, Harding GFA. (1997). Magnetoencephalographic evidence for non-geniculostriate visual input to human cortical area V5. Neuropsychologia, 35: 1139-1146.

Holtzman JD. Interactions between cortical and sub-cortical visual areas: evidence from human commissurotomy patients. Vision Research 1984, 24:801-813.

Kapoula Z, Bucci MP, Eggert T, Garraud L. Impairment of the binocular co-ordination of saccades in strabismus. Vision Research 1997; 37:2757-2766.

Kapoula Z, Bucci P. Distribution-dependent saccades in children with strabismus and in normals. Experimental Brain Research 2002; 143: 264-268.

Kapoula Z, Bucci MP, Eggert T, Zamfirescu F. Fast disconjugate adaptations of saccades in microstrabismic participants. Vision Research 1996, 36:103-108.

Kapoula Z, Eggert T, Bucci M.P. Immediate saccade amplitude disconjugacy induced by unequal images. Vision Research 1995, 35: 3505-3518.

Kapoula Z, Hain TC, Zee DS, Robinson DA. Adaptive changes in post-saccadic drift induced by patching one eye. Vision Research 1987, 27:1299-1307.

Lemij HG, Collewijn H. Short-term nonconjugate adaptation of human saccades to anisometropic spectacles. Vision Research 1991, 31: 1955-1966.

Olivier E, Dorris MC, Munoz DP. Lateral interactions in the superior colliculus, not an extended fixation zone, can account for the remote distractor effect. Behavioural and Brain Sciences 1999, 22:694-695.

Pöppel E, Held R, Frost D. Residual visual function after brain wounds involving the central visual pathways in man. Nature 1973, 243:295-296.

Rafal R, Smith J, Krantz J, Cohen A, Brennan C. Extrageniculate vision in hemianopic humans: Saccade inhibition by signals in the blind field. Science 1990, 250:118-121.

Sanders MD, Warrington EK, Marshall J, Weiskrantz L. 'Blindsight': Vision in a field defect. Lancet 1974, 20:707-708.

Schor CM. Binocular sensory disorders. In D. Regan (ed) Vision and visual dysfunction: vol. 9: Binocular vision. London. Macmillon Press. 1991, pp179-223.

van der Steen J, Bruno P. Unequal amplitude saccades produced by aniseikonic patterns: effects of viewing distance. Vision Research 1995, 35: 3459-3473.

Walker R, Deubel H, Schneider WX, Findlay JM. Effect of remote distractors on saccadic programming: evidence for an extended fixation zone. Journal of Neurophysiology 1997, 78:1108-1119.

Walker R, Mannan S, Maurer D, Pambakian ALM, Kennard C. The oculomotor distractor effect in normal and hemianopic vision. Proceedings of the Royal Society (London) B, 2000, 267:431-438.

Weiskrantz L. Consciousness lost and found. Oxford University Press. 1987, pp16-23.

Weiskrantz L, Warrington EK, Sanders MD, Marshall J. Visual capacity in the hemianopic field following a restricted occipital ablation. Brain 1974, 97:709-728.

Wolfe JM. Briefly presented stimuli can disrupt constant suppression and binocular rivalry suppression. Perception 1986, 15:413-417.

Zihl J. 'Blindsight': Improvement of visually guided eye movements by systematic practice in patients with cerebral blindness. Neuropsychologia 1980, 18:71-77.

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Participant	Age (years)	VA		Strabismus	PCT (Δ)	Density
		RE	LE			
1	62.8	-0.1	0.2	left XT	2 BI	15
2	20.2	0.0	-0.1	right ET	6 BO	10
3	22.8	0.0	-0.1	right ET	6 BO	8
4	41.0	-0.1	0.0	left XT	12 BI	6
5	39.5	0.4	-0.1	right ET	12 BO	14
6	19.4	-0.1	0.1	left XT	18 BI	5
7	59.0	0.1	0.2	Left ET	2 BO	12
8	19.0	0.1	0.6	Left XT	8Δ BO	10
Mean	**35.5**					
SD	**18.0**					

Table 1: Participant details - participants 1 to 6 took part in Experiment 1; participants 3 to 8 took part in Experiment 2. VA = visual acuity measures using Bailey Lovie logMAR chart, RE = right eye, LE = left eye, ET = esotropia, XT = exotropia, PCT = measurement of the angle of deviation fixing at 1.14metres recorded in prism dioptres (Δ) using the prism cover test (PCT), BO = prism base out, BI = prism base in, Density = density of suppression measured with Bagolini filter bar (Sbisa bar),

a) 4° target

Participant	Distractor at fixation in the strabismic eye (ms)	Maximum increase (ms)	Position of maximum increase	Expected location of anatomical fovea
1	25.3	25.3	0	-1
2	15.8	27.6	-4	-3
3	11.7	16.8	-4	-3
4	-0.9	12.7	-6	-6
5	1.6	24.3	-6	-6
6	19.4	37.4	-10	-9
Mean	**12.1**	**24.0**		
SD	**9.3**	**7.9**		
SE	**3.8**	**3.2**		

b) 8° target

Participant	Distractor at fixation in the strabismic eye (ms)	Maximum increase (ms)	Position of maximum increase	Expected location of anatomical fovea
1	21.4	21.4	0	-1
2	18.9	47.2	-4	-3
3	-6.8	10.4	-6	-3
4	-3.0	13.9	-6	-6
5	-1.8	19.6	-2	-6
6	-3.9	16.7	-4	-9
Mean	**4.1**	**21.5**		
SD	**12.5**	**13.2**		
SE	**5.1**	**5.4**		

Table 2: From Experiment 1 difference in saccade latency with and without distractors presented to the strabismic eye for 6 strabismic participants with suppression. Positive values represent an increase and negative values a decrease in saccade latency with distractors. SD = standard deviation, SE = standard error.

Participant	Fixing eye		Strabismic eye	
	Convergent	Divergent	Convergent	Divergent
3	-	-	-	-
4	-	-	-	-
5	-	-	**	-
6	***	**	-	-
7	***	***	***	***
8	-	-	***	*

Table 3: Summary of significance levels of z scores for individual strabismic participants. 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 participant 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.

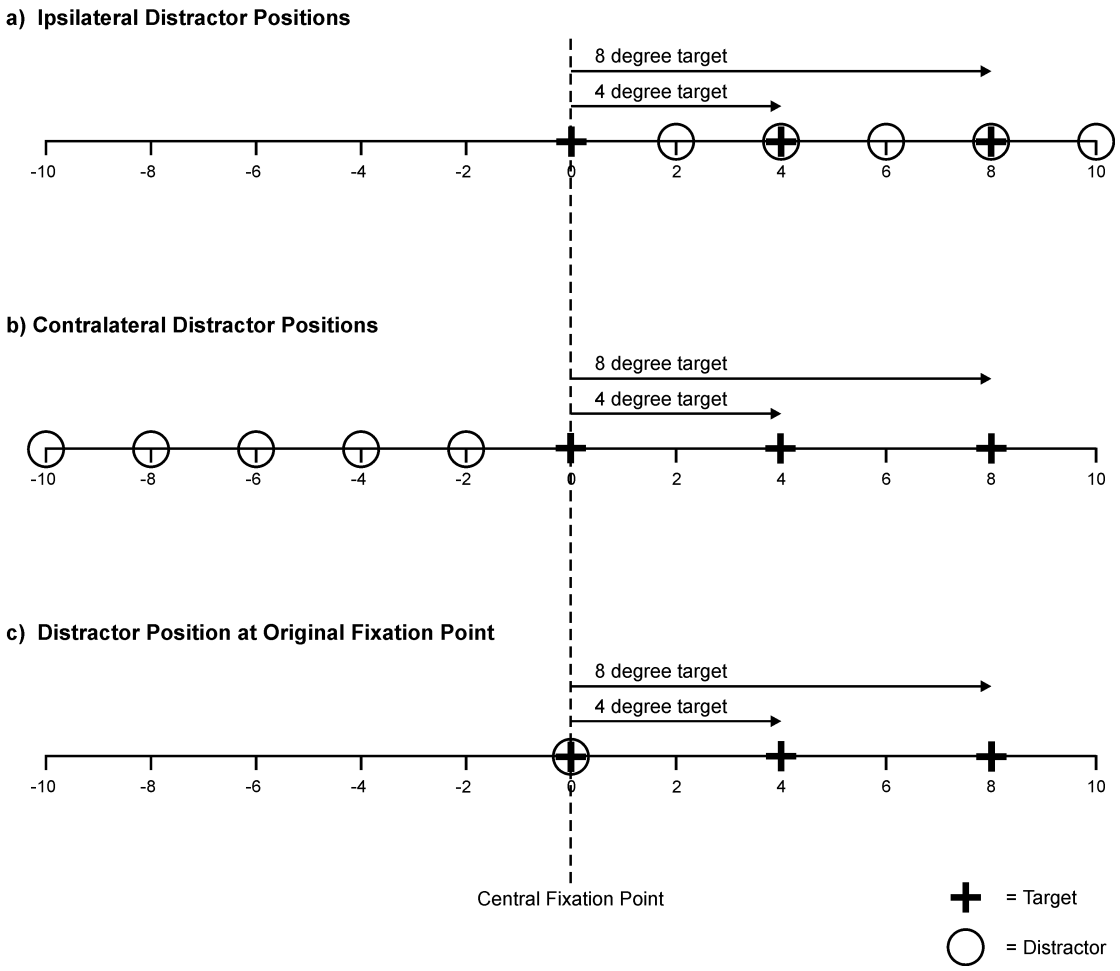

Figure 1: Schematic diagram of target and distractor positions.

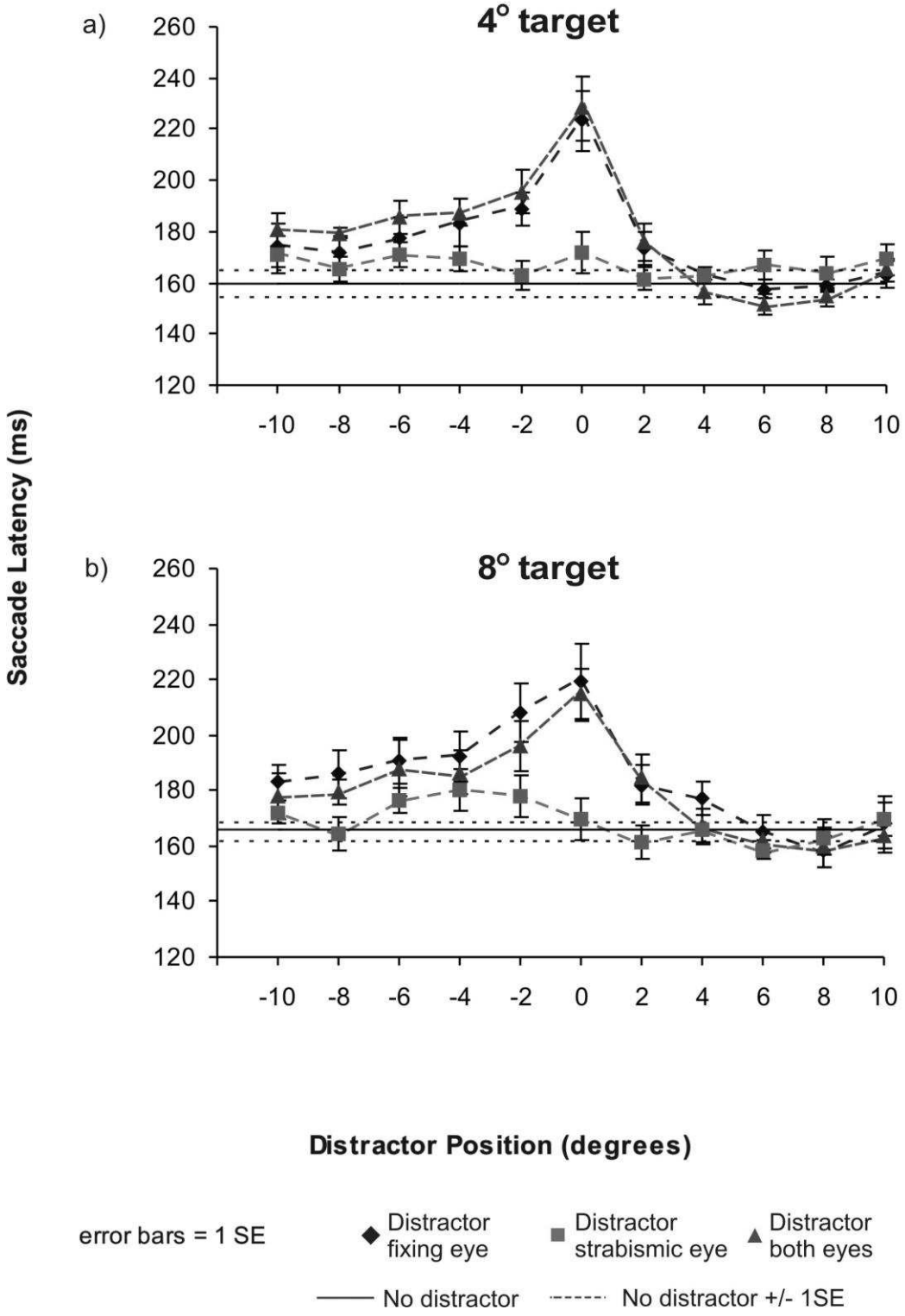

Figure 2: Effect of distractors on saccade latency, a) target presented at 4°, b) target presented at 8°. Pooled data for six participants with constant strabismus and suppression.

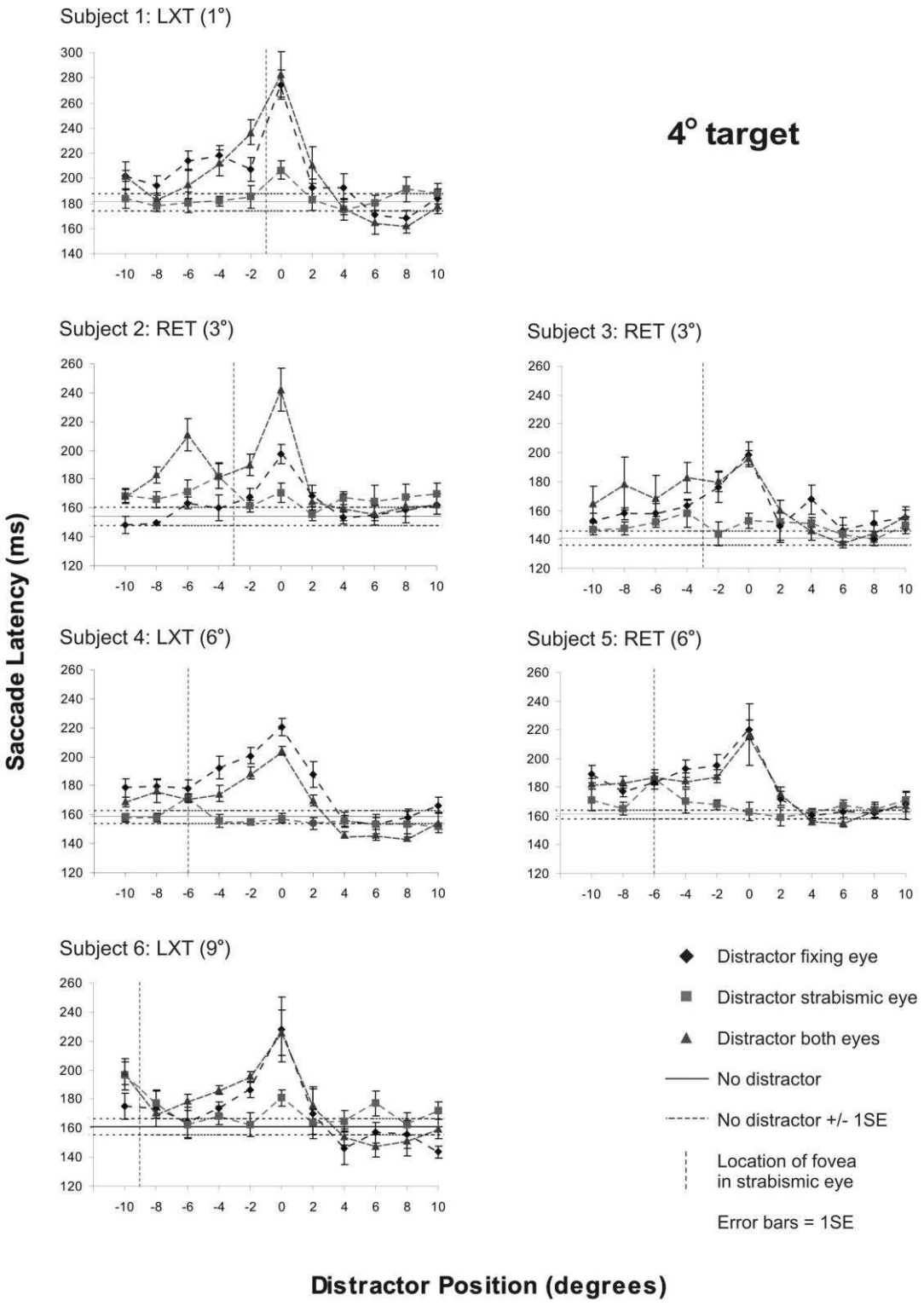

Figure 3: The effect of distractors presented simultaneously with a 4° target to the fixing eye, strabismic eye and both eyes, on saccade latency for six strabismic participants with suppression. Zero distractor position represents the original central fixation point, negative values represent contralateral distractors and positive values represent ipsilateral distractors. The data for participant 1 is shown with a different axis range due to longer latencies than the other participants. SE = standard error.

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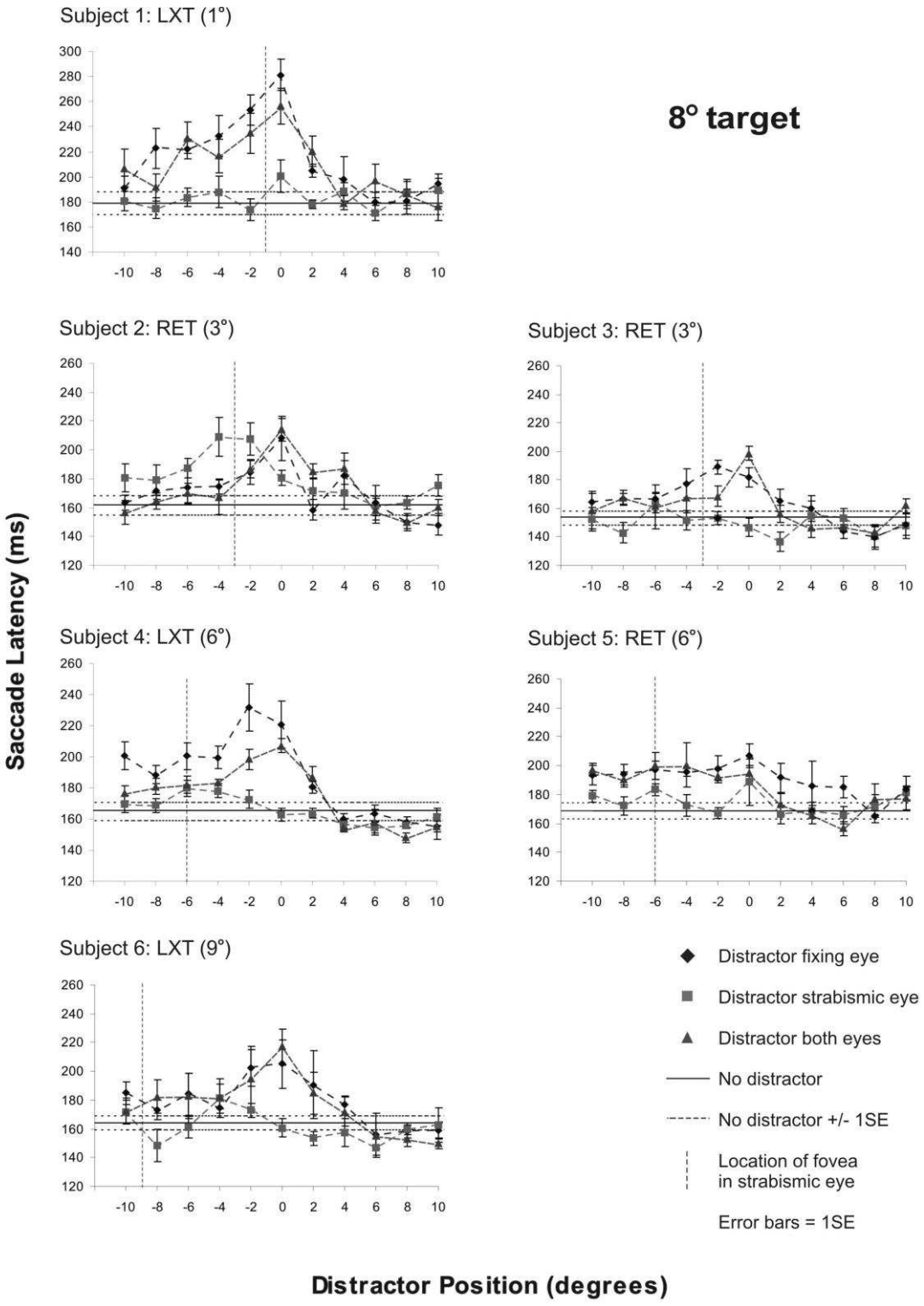

Figure 4: The effect of distractors presented to the fixing eye, strabismic eye and both eyes, (simultaneously with an 8° target), on saccade latency for six strabismic participants with suppression. Zero distractor position represents the original central fixation point, negative values represent contralateral distractors and positive values represent ipsilateral distractors. The data for participant 1 is shown with a different axis range due to longer latencies than the other participants. SE = standard error.

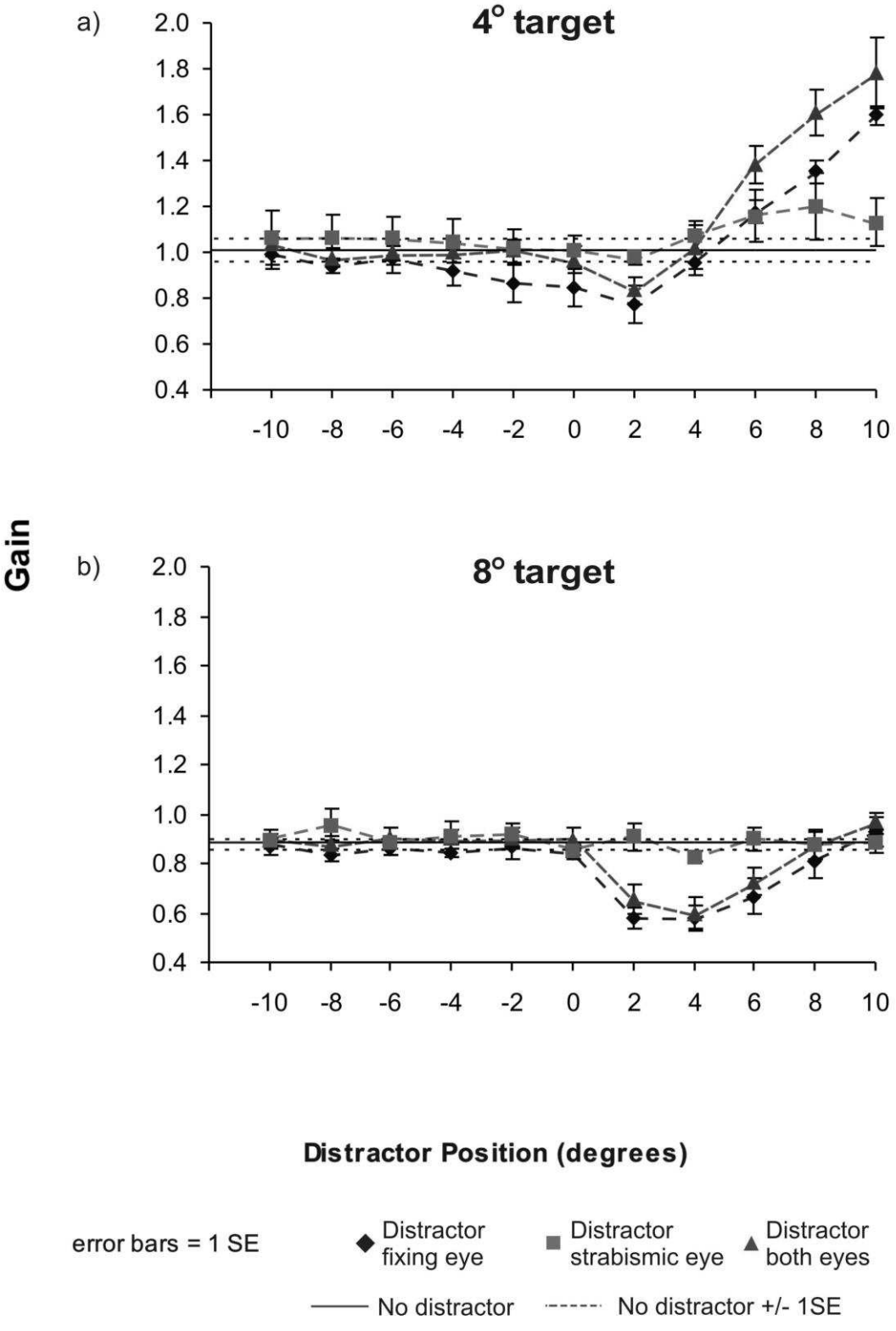

Figure 5: Effect of distractors on saccade gain, a) target presented at 4°, b) target presented at 8°. Pooled data for six participants with constant strabismus and suppression.

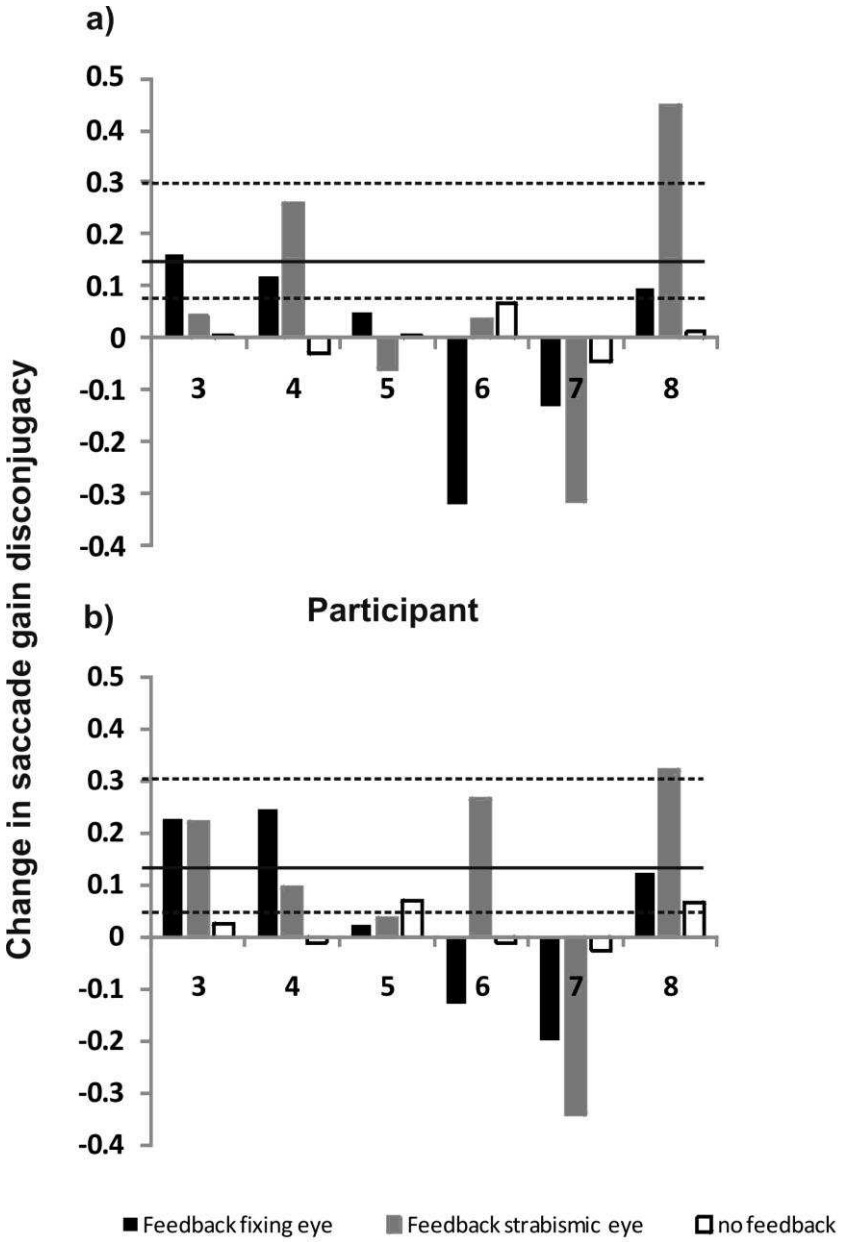

Figure 6: Change in saccade gain disconjugacy in the post-adaptation phase compared to the pre-adaptation phase for a) convergent disparity and b) divergent disparity. Results of individual strabismic participants are plotted. The mean change in disconjugacy for the BSV participants is represented as the solid black line. The dotted lines indicate the range of results in the BSV group.

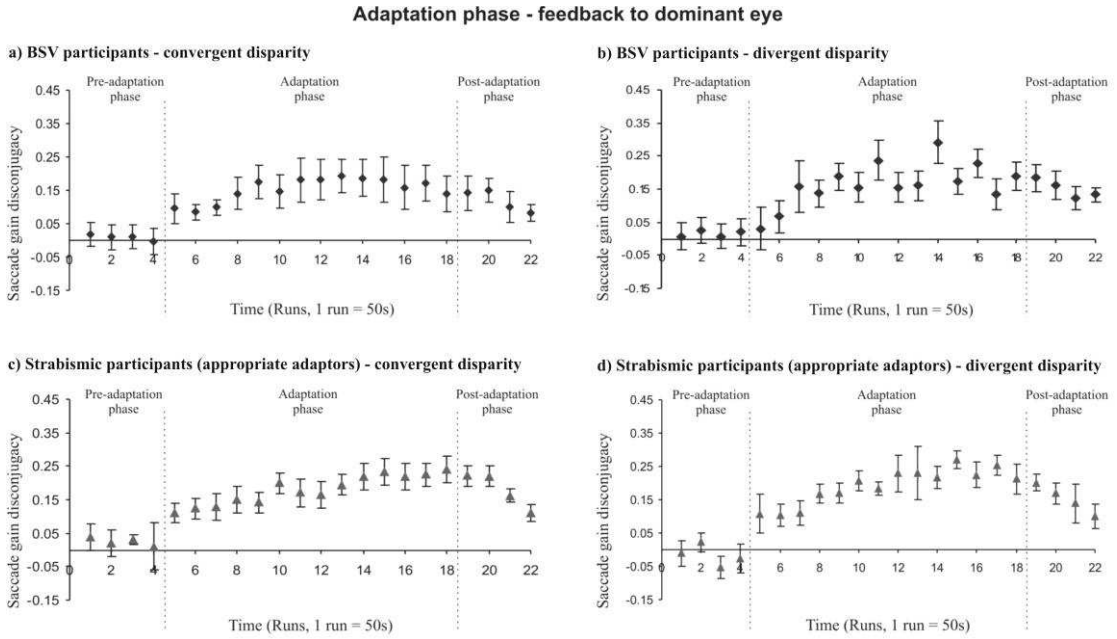

Figure 7: Mean saccade disconjugacy over the time course of the three experimental phases for: a&b) 3 participants with normal BSV and c&d) pooled data from the 3 strabismic participants who demonstrated appropriate disconjugate adaptation with feedback to the dominant fixing eye (participants 3,4&8)

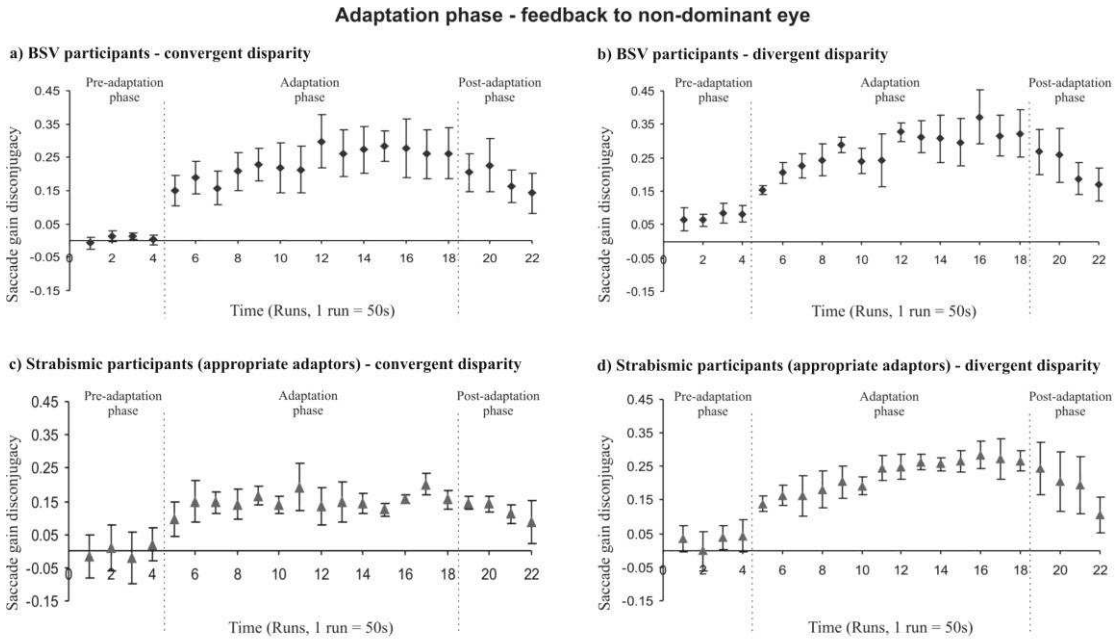

Figure 8: Mean saccade disconjugacy over the time course of the three experimental phases for: a&b) 3 participants with normal BSV and c&d) pooled data from the 3 strabismic participants who demonstrated appropriate disconjugate adaptation with feedback to the non-dominant strabismic eye (participants 3,4&8)

Appendix

Experiment 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 participants with suppression perceived the distractor presented to the strabismic eye for 200ms during the saccade task the following experiment was carried out after Experiment 1. It was considered appropriate to perform this current experiment following the distractor experiment as participants 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.

Method

Participants

Five of six strabismic participants with suppression described in Experiment 1 (participants 2, 3, 4, 5 and 6) and two adults with normal BSV were tested.

Procedure

The participants 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 participants 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. 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 1.

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 participants.

The participants 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.

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 participant, of 10 trials in each distractor position is shown in Figure 9. The horizontal black line represents the number of false positive responses in the no distractor condition.

From Figure 9 it is clear that the binocular participants 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 participants 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'. These results show high d' values for all distractor positions for all 3 distractor conditions in both of the binocular participants. This is in contrast to all of the five strabismic participants 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.

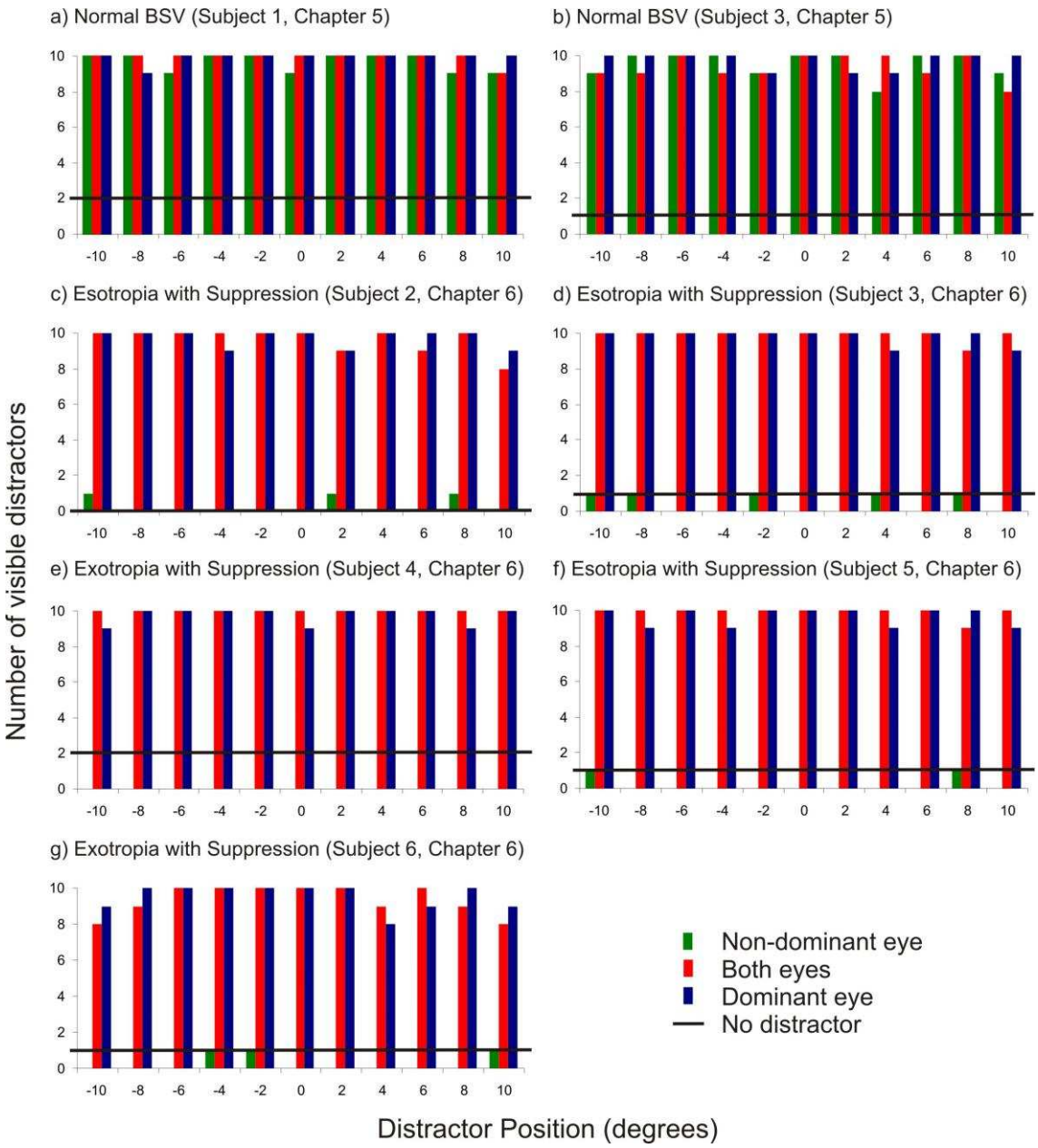

Figure 9: The number of visible distractors at each eccentricity for 2 participants with normal BSV (a&b), and 5 strabismic participants with suppression (c to g). Responses were recorded from each participant using a joystick to indicate when they were aware of a distractor at any location. The participants 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 Experiment 1. The black horizontal line represents the number of no distractor presentations in which a visible response was made (i.e. false positives).

Conclusion

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

The response to distractors presented in the strabismic eye reported in Experiment 1 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.

Experiment to determine awareness of the distractor

It is possible that although participants reported lack of perception of the distractor that they may have been sub-consciously aware of the distractor. Such responses have been reported in participants 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 participant with a visual field defect following removal of a tumour that had invaded V1. The participant 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 participants 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.

Method

Participants

The same seven participants described above were studied.

Procedure

The experimental set-up, target and distractor stimuli were identical to that described in Experiment 1. The only difference in procedure was the instructions given to the participants. 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.

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 10 shows the number of left responses out of 10 trials, for each participant, 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 participant's bias in response when nothing was visible to them.

From Figure 10 a and b it is clear, generally, that the two binocular participants correctly indicated the direction of the distractor under all three viewing conditions. Figure 6.8 c to g shows that in the strabismic participants 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 participants responded similarly to their response in the no distractor condition. They either randomly guessed the side giving approximately 50% of responses in each direction (participants 4 and 5) or showed a bias by maintaining a single direction for the majority of presentations (participants 2, 3 & 6).

Conclusion

The results suggest that the distractor was highly visible and correctly localised by binocular participants under all viewing conditions and by strabismic participants when presented to both eyes or to the fixing eye. However, in strabismic participants 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.

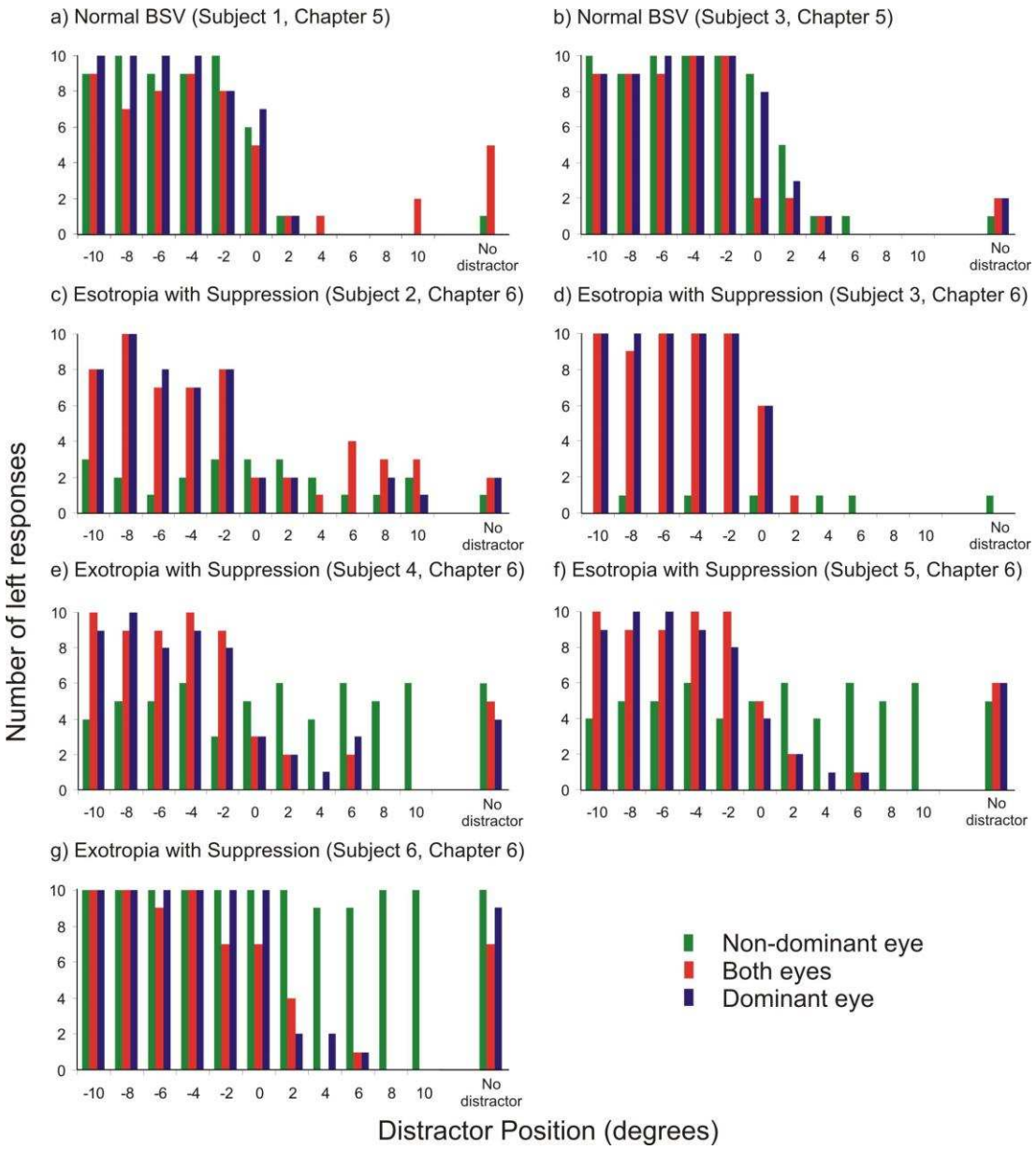

Figure 10: The number of joystick responses to the left at each eccentricity for 2 participants with normal BSV (a & b), and 5 strabismic participants with suppression (c to g). Results are shown with distractors presented to the dominant eye, non-dominant eye and to both eyes. Negative distractor positions 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 participant 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 participant's guessing bias. The participants 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 experiment (Experiment 1).