Fixational Eye movements in Strabismic amblyopia

by

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AUTHOR'S DECLARATION

I hereby declare that I am the sole author of this thesis. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners.

I understand that my thesis may be made electronically available to the public.

Abstract

Purpose: To test the hypothesis that the fixational stability (FS) of the amblyopic eye (AME) in strabismics will improve when binocular integration is enhanced through ocular alignment and inter-ocular suppression is attenuated by reducing the contrast to the fellow eye (FFE).

Methods: 7 strabismic amblyopes (age: 30.8±9.7 yrs) (5 esotropes and 2 exotrope) (VA: AME=0.50±0.30; FFE=-0.12±0.04) showing clinical characteristics of central suppression were recruited. Suppression was then attenuated by a balance point procedure where the contrast to the FFE was reduced in order to maximize binocular integration during a global motion task (GMT) (Baker, 2007). In one case the balance point could not be determined, and the participant was excluded. Ocular alignment was established with a haploscope. Participants dichoptically viewed similar targets [a cross (2.3°) surrounded by a square (11.3°) visual angle] set at 40cm. Target contrasts presented to each eye were either equal (EQ) or attenuated in the FFE (UNEQ) by an amount defined by the GMT. FS was measured over a 5 min period (Viewpoint® Eye Tracker, Arrington Research) and quantified using bivariate contour ellipse areas (BCEA) in four different binocular conditions; unaligned/EQ, unaligned/UNEQ, aligned/EQ and aligned/UNEQ. FS was also measured in 6 control subjects (Age: 25.3±4 yrs; VA: -0.1±0.08).

Results: Alignment of the AME was transient and lasting between 30 to 80 seconds. Accordingly, FS was analyzed over the first 30 seconds using repeated measures ANOVA. Post hoc analysis revealed that for the amblyopic subjects, the FS of the AME was significantly improved in aligned/EQ **(p=0.015)** and aligned/UNEQ **(p=0.001).** FS of FFE was **not** different statistically across conditions. $\mathrm{BCEA}_{\mathbf{FFE}}$ & $\mathrm{BCEA}_{\mathbf{AME}}$ were then averaged for each amblyope in the 4 conditions and compared with normals. This averaged BCEA (reduced FS) was significantly greater **(p=0.0205)** in amblyopes compared to controls except in the case of alignment coupled with reduced suppression (aligned/UNEQ) **(p=0.1232).**

Conclusion: Fixation stability in the amblyopic eye of strabismics appears to improve directly with the degree of binocular integration. The hypothesis is therefore retained.

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Dedication

This thesis is dedicated to the
Almighty God
and
to my beloved *family members*
(My dad, mom, brother, sister-in-law and my niece Rakshanaa).

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Chapter 1

REVIEW ON BINOCULAR VISION OF NORMALS AND STRABISMICS

1.1 Binocular vision in normals:

Imagine an object at a suitable distance in front in the mid plane of the head. If the eyes are properly aligned and if the object is fixated binocularly then the image would fall on corresponding retinal points. Thus the *corresponding retinal points* are the retinal element/retinal point which when stimulated simultaneously will give rise to a single binocular percept [21,26,47,56]. Each retinal element localizes the object in a specific direction and it is relative to the fovea (the retinal area with highest visual acuity). Thus, the corresponding retinal points can also be defined as the points that share the same visual direction. In normal binocular vision, therefore, both foveas have same visual direction (corresponding retinal points) and the phenomenon is called *normal retinal correspondence* [56].

The corresponding retinal points are distributed throughout the retina and locus of these retinal points, in visual space, is called *horopter*. In other words, any point in the horopter would stimulate corresponding retinal points. In visual space, this horopter forms an arc of a circle called *Vieth Muller Circle* [21,56]. This is the ideal or theoretical horopter. It is a circle which passes through nodal points of the eyes and the fixation point (figure: 1-2). There is a small area in front and back of the horopter in which single vision is present is called *Panum's fusional area*. This area is about 0.5° around the horopter [47,48]. When eyes are fixating on an object, there is always a minute variation in binocular vision which is within Panum’s fusional area and this is called *fixation disparity* [33,40]. Panum’s fusional area and fixation disparity are responsible for stereoscopic vision [56].

In figure: 1-1, the visual axes are converged at the fixation point. The point A which is nearer to the observer than the horopter produces crossed retinal disparity (crossed images). This is called crossed disparity (images) because, with monocular viewing, midline of the point A appears on the opposite side of the fixation point. This is also known as convergent disparity. The point B is beyond the horopter and produces uncrossed disparity. This is called uncrossed disparity because with monocular viewing, midline of the point B appears on the same side to the fixation point. If these disparities lie outside the Panum’s fusional area, they will induce motor fusion i.e. fusional vergence eye movements; crossed disparity induces convergent eye movement whereas uncrossed disparity induces divergent eye movement. Thus each retinal point has some *retinomotor value.* This retinomotor value increases from the center towards the periphery. The fovea is called the *retinomotor center* or *retinomotor zero point* because, once the image is on fovea, there is no need for any further eye movement[21,56].

However, to perceive the images falling on the foveas and other corresponding retinal points as a single percept, sensory fusion is required and it takes place in the visual cortex[21,47,56]. The term sensory fusion is defined as unification of excitations from corresponding retinal images into single visual percept. In other words, the stimulus to sensory fusion is excitation of corresponding retinal points [56]. For sensory fusion, images not only must fall on corresponding retinal points but also must be in similar size, contour and brightness[46]. The simultaneous stimulation of non-corresponding retinal points by a similar object induces double vision/*diplopia.* But the ability to align the eyes in such a manner (i.e. move it in opposite direction – fusional vergence) to maintain the sensory fusion is termed as *motor fusion.* Thus the retinal disparity is stimulus for motor fusion. For motor fusion, again the images must be similar in size and fall outside the Panum's area.

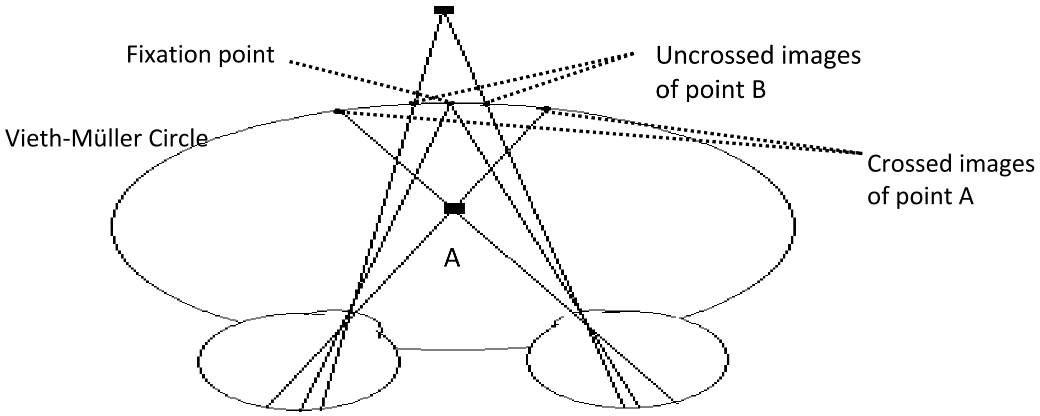


Figure 1-1: Crossed and uncrossed disparity.

Vieth Muller circle is the circle passing through point of fixation and the nodal points. The images of point A are crossed because their visual lines cross inside the horopter. The images of point B are uncrossed because their visual lines cross beyond the horopter [Image duplicated from Howard and Rogers, 1995].

Binocular Rivalry:

When dissimilar contours are presented to corresponding retinal points, fusion is not possible but a binocularly-based rivalry may be observed. In other words, such excitations are localized in the same visual direction which results in conflict or confusion. Rivalry could also be induced by uniform surface of different colors (color rivalry) and unequal luminance of the two targets. Our visual system responds to such rivalries by suppressing one of the images. Which of the images is suppressed depends on the dominance of one eye rather than the quality of images like contour, luminance or color [8,56].

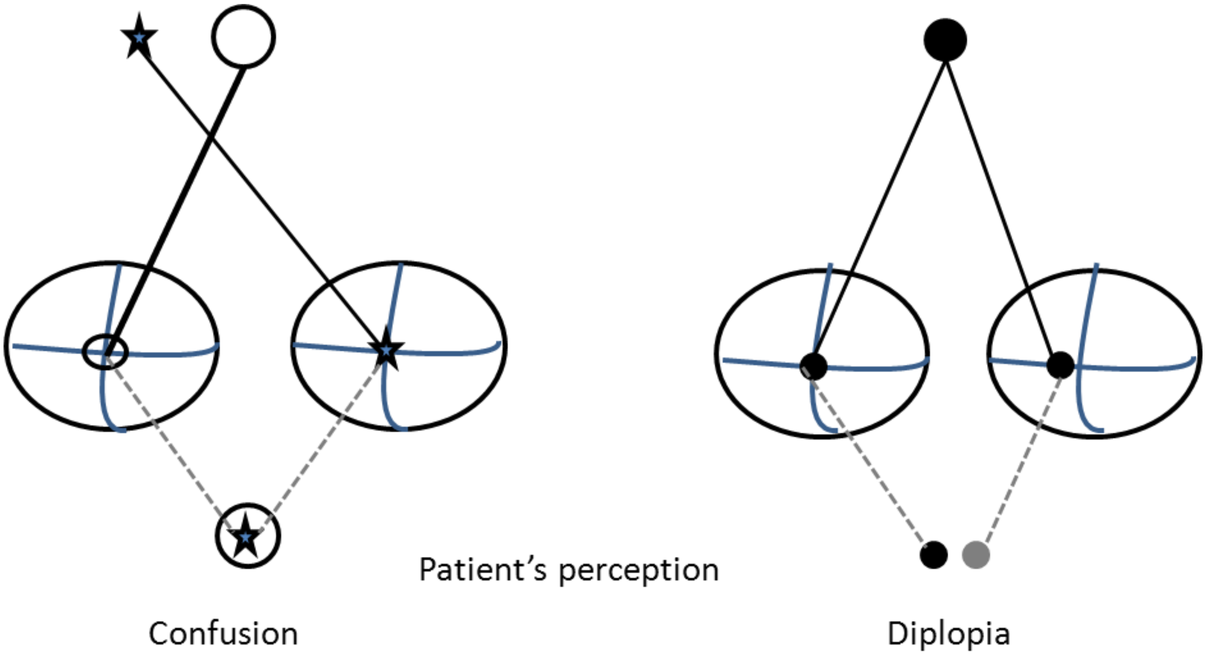


Figure 1-2: Confusion and Diplopia

a) explains the phenomenon of confusion where dissimilar images fall on corresponding retinal points and, b) explains the phenomenon of diplopia where similar images stimulating non corresponding retinal points (Image adapted from Von Noorden, 2002)

1.2 Binocular vision in strabismus:

The lack of alignment of the primary lines of sight with the object of regard in strabismus leads to the object being imaged on the fovea of one eye and a non foveal point of the turned eye. If normal correspondence is present, then it results in diplopia and confusion (Figure: 1-2). The former arises due the image of the object of regard falling on non-corresponding points whereas the latter due to differing images falling on the fovea. However, if the strabismus is long standing then the visual system can invoke one of two sensory adaptations which serve to reduce the diplopia and confusion: anomalous retinal correspondence (ARC) or suppression. Small angle strabismics usually adapt to ARC whereas large angle strabismics adapt to suppression [24]. Understanding of these adaptations has been primarily based in clinical literatures [3,21,24,56].

However, existence of such adaptations is really debatable. For instance, Schor (1991) points out that it is remarkable that ARC as described could exist. In the case of infantile esotropia where the strabismus has developed in early developmental ages, there would be very little opportunity for the underpinning of correspondence between two eyes and the development of binocular vision through anomalous correspondence.

1.2.1 Anomalous retinal correspondence (ARC):

ARC is defined as *the perception of foveal stimuli in the two eyes in separate visual directions.* In other words, it describes a situation where apparently the correspondence of the deviated eye is compromised such that the non-foveal point in the deviated eye is given the same visual direction as that of the fovea of the fixing eye [56]. Thus diplopia and confusion are avoided. The angle separating this corresponding point and the anatomical fovea of the deviating eye is called *angle of anomaly (A).* If the angle of anomaly (A) equals the objective angle of strabismus, then it is termed as Harmonious ARC (HARC). If the angle of anomaly (A) did not equal the objective angle (H), then it is termed as Unharmomious ARC and the retinal disparity equal to the difference (H-A) could stimulate diplopia. This difference in the angle is called subjective angle of strabismus (S) [24,47,56]. ARC can be very variable and at times it may co-exist with suppression. Clinical tests are always biased where the Bagolini Striated glass test (description in the section 1.2.2.3) will show ARC more frequently than

Worth's four dot test. As with suppression, ARC can be altered with changes in luminance and contrast [6].

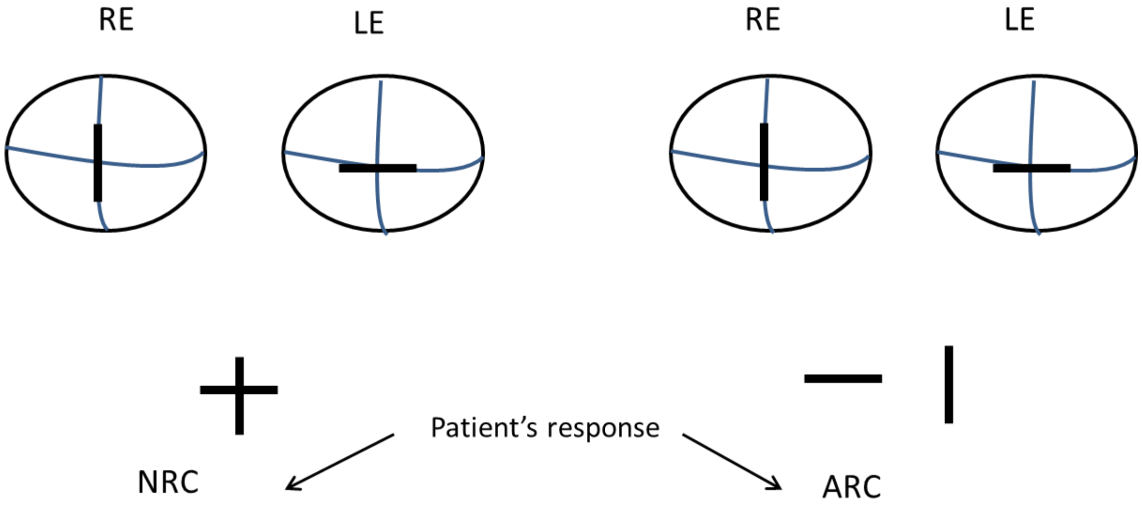


Figure 1-3: Normal and Anomalous retinal correspondence

A) After Image test showing Normal retinal correspondence where the foveas of the two eyes having same visual direction and B) after image test showing abnormal retinal correspondence where the foveas of the two eyes have different visual direction (adapted from Von Noorden, 2002).

1.2.1.1 Theories of ARC:

The main question is how does an elaborate system of ARC evolve where correspondence can be adjusted with each position to keep both retinal images with same visual direction? There are two schools of thought regarding ARC. One of these schools of thought thinks that ARC is a sensory adaptation to avoid diplopia/confusion (ambiocular vision) whereas the other thinks that ARC is a primitive form of vision (utrocular vision) found normally in vertebrates with complete decussation of the visual pathways.

1.2.1.1.1 Utrocular vision:

Schor (1991) has pointed out the elegant theory of Walls (1951). Based upon his deep understanding of comparative vision, it is postulated that what is called ARC could really represent a regression to utrocular vision such as that experienced by a species that has no binocular vision. In lower vertebrates, the visual cortical hemisphere receives inputs completely from the contralateral eye and also they have laterally placed eyes which support a form of panoramic vision. The visual directions of the two eyes are compared more egocentrically (Egocentric visual direction refers to the visual direction of an object in space relative to oneself, rather than the eyes). Schor (1991)[47] has stated neurophysiological and psychophysical correlates to substantiate that ARC is a form of utrocular form of vision.

1.2.1.1.2 Ambiocular vision:

The hypothesis of utrocular vision cannot be fully accepted as the subjects with ARC do exhibit binocular functions like reduced stereopsis and vergence eye movements. So, the other school of thought thinks that ARC is a sensory adaptation which has limited form of binocular vision and compares visual direction more oculocentrically, rather egocentrically as in utrocular vision. Correspondence shift and enlarged fusional area are the two organization of binocular vision that substantiates ARC is an ambiocular vision.

Correspondence shift:

This is a classical theory of ARC suggested by Von Noorden that ARC is a shift of the subjective visual direction of the non-fixating eye relative to those of fixating eye [56]. This implies that, when one eye is constantly deviated, it leads to suppression in its central field of vision. The correspondence between the foveas is lost and the visual direction of the non-fixating eye shifts. As a result, the fovea of the fixating eye acquires the correspondence with the peripheral region of the non-fixating eye. He also added that ARC adapts the sensory system to the abnormal motor condition created by deviation of the eye in order to restore some of the binocular cooperation. In other words, if the fovea of the fixating eye acquires a common visual direction with a region of the non-deviated eye where the fixation point is imaged, then the deviation is neutralized sensorially and adaptation is successful [56].

Enlarged binocular fusion:

It can be thought of as a separate school of thought about ARC (indeed about single vision in strabismus). It says that strabismics usually have enlarged Panum's fusion area [1–3,47]. As mentioned earlier, the PFA in normal subjects will be 0.5°. However, Schor (1991)[47] reported that the area has varying dimensions which depends upon the spatial frequency of the fusion stimuli. PFA varies from 20' when the tested with 2cpd or higher spatial frequency to 6° when tested with spatial frequency of 0.1 cpd. So, if this area extends and accommodates the angle of strabismus, then the strabismic will have a single vision with normal correspondence.

1.2.1.1.3 Multiple processes

From the above short review, ARC appears to have properties which cannot be accounted for by only one of the above theories [47]. Thus, it is hypothesized that ARC is a combination of utrocular and ambiocular vision[47]. In the central visual field where stimuli fall within the visual axes of strabismus patients, there is no chance for ambiocular vision (correspondence shifts or enlarged binocular fusion) as the image is processed in the opposite cortical hemisphere. Rather an utrocular vision is more likely in the central field. In the peripheral field, it is more likely to have ambiocular vision (i.e. correspondence shift and enlarged fusion) as the image is processed in the same cortical hemisphere.

1.2.2 Suppression:

When binocular fixation is maintained at a fixed distance, objects that are closer and farther away stimulate non-corresponding retinal points and induce *physiological diplopia.* However, our visual system eliminates/ignores the physiological diplopia and this process is referred as *suspension.* As mentioned earlier, a person with strabismus and normal retinal correspondence experiences two disturbing factors, diplopia (referred to as *pathological diplopia)* and confusion. Both pathological diplopia and confusion are eliminated by a regional suppression of one ocular image [23,47], suppression is strictly limited to binocular vision. Suppression maybe alternating or strictly monocular depending on the type of fixation the patient has. In alternating strabismus, the suppression scotoma is found in the deviating eye only. Unlike suppression in constant strabismus, the suppression in alternators might not lead to amblyopia, as both foveas have their turn to fixate at the target.

Jampolsky (1955) has listed out the characteristics of suppression in strabismus: 1) *the suppression is always confined to a specific region* and this can be easily demonstrated by plotting the functional suppression scotoma using various methods, e.g. haploscopic method by Travers (1934) and rotary Risley prisms by Jampolsky (1955), 2) *suppression always exists under binocular condition* since there is no need to suppress when the double vision is eliminated by closing one eye, 3) *suppression is demonstrated primarily for similar contours,* 4) *requires a short latent period to become manifest* (75-150ms) and 5) *suppression differs significantly before the visual development (i.e. before approx. 6 years of* *age) and after visual adulthood.* The ability to change/establish a new pattern of suppression is reduced after 6 years of age. Thus acquired diplopia e.g. due to paresis of an ocular muscle, rarely develop suppression. But, if desired, they can consciously "ignore" which is not true suppression.

1.2.2.1 Physiological basis of suppression:

Suppression can be induced in binocular individuals. Two processes are well known; 1) binocular rivalry and 2) dichoptic masking. Binocular rivalry is achieved by imaging dissimilar images onto the foveal and other corresponding retinal points in the two eyes. In this situation the dissimilar images are typically alternately suppressed indicating an equal level of dominance between the eyes [14,56]. In large angle strabismus where binocular integration is not possible, binocular rivalry appears to be the possible physiological basis for developing suppression. Dichoptic masking refers to a physiological process whereby a stimulus of a given contrast presented to one eye can prevent the detection of a lower contrast but otherwise identical stimulus presented to the other eye [14]. It has been proposed as a physiological basis of suppression in the anisometropic and small angle strabismus [15,46].

1.2.2.2 Neurophysiological Site of Suppression:

After the decussation of nasal fibers from the retina of each eye (at optic chiasm), the signals from nasal retina of the contralateral eye and temporal retinal of the ipsilateral eye reach lateral geniculate nucleus (LGN). From the LGN, the signals reach cerebral cortex especially striated cortex (area 17)[26]. The striate cortex is six layered (Layers 1, 2, 3, 4 [a, b, c], 5 and 6) and the fibers coming from the LGN reaches the layer 4c. There are feedback signals fed back into the LGN called cortico-geniculate pathway. The layer 4c divided further into two layers; alpha (α) where the fibers from the magnocellular pathway reach and beta (β) where the fibers from the parvocellular pathway reach. This 4c layers also comprises ocular dominance columns [22,26]. Above and below this layer 4c, there are cells which could be influenced from the non-dominant eye and these cells are called *binocular cells/neurons*. The reduction of these binocular cells due to monocular deprivation or the inhibition due to ocular misalignment appears to be the physiological reason behind the suppression [57]. So it is a currently accepted notion that the amblyopia is of cortical origin where the inputs from the two eyes combine. However, a study [19]using functional magnetic resonance imaging (fMRI), found that the earliest functional deficit noted was in fact at the LGN. But it is still unclear whether the deficit is within the LGN or due to the defective feedback from the cortical area (because of those structural changes) [19].

1.2.2.3 Clinical measures of suppression:

It is well established that in amblyopia (Section 1.3), one eye has higher sensory dominance over the other eye (i.e. intraocular suppression). There were few traditional clinical tests used to check and quantify the sensory dominance (suppression) like Worth Four Dot test (WFDT) and Bagolini Striated Glass test (BSGT).

Worth Four Dot Test (WFDT):

Under normal room illumination, with Red-green anaglyphs (red filter over the right eye and green filter over the left eye), the participants are asked to look at the target (red light at the top, green on both side and white at the bottom). The perceived response will give information of sensory status (figure: 1-4).

Bagolini Striated glass test (BSGT):

The striated glasses are plano glasses without any refractive power and they have fine parallel lines that do not alter the visual acuity. The striated glasses are placed at 45° and 135° before each eye and when a participant fixates at a point light source through these striated glasses, it is perceived as two orthogonal streaks with a point light source in the middle as shown in the Figure: 1-5. The perceived response will give information about the sensory status (figure: 1-5).

Using the above mentioned tests, we can quantify depth of suppression with the help of neutral density (ND) filters [6,32]. The density of ND filters is increased until the fusion response is reported and the grade of density at which the fusion response elicited represents the depth of suppression. Cadera et al (1983)[6] suggested a modified method to quantify the depth of suppression in strabismic amblyopes using neutral density filters. A dense ND filter is placed over the preferred eye, so that the amblyopic eye would fixate at the target. Then the grade of density of ND will be gradually decreased until the fixation shifts back to the preferred eye. This method is indeed different from the previously mentioned methods, as it is involved with the motor response rather than the perceived response (sensory).

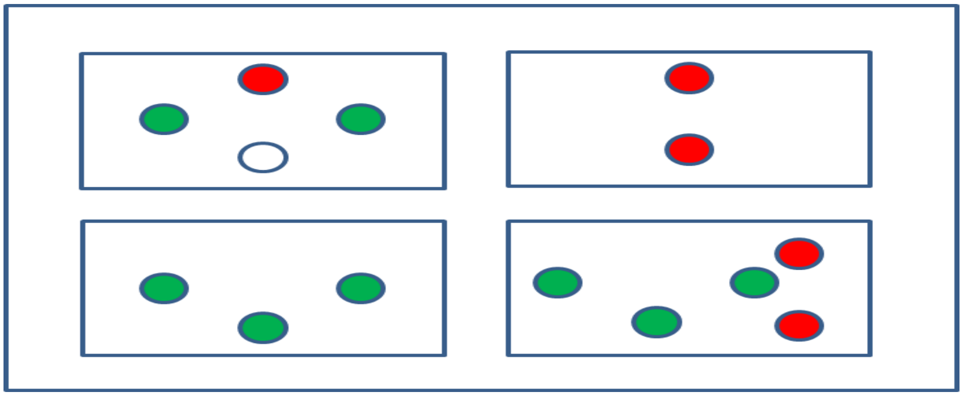


Figure 1-4 Different precieved response of Worth four dot test

The figure showing the possible perceived response, b) fusion: usually seen in orthophoria or anomalous retinal correspondence, c) Left eye suppression, d) Right eye suppression and e) uncrossed diplopia seen in esotropia. (Image adapted from von Noorden, 2002)

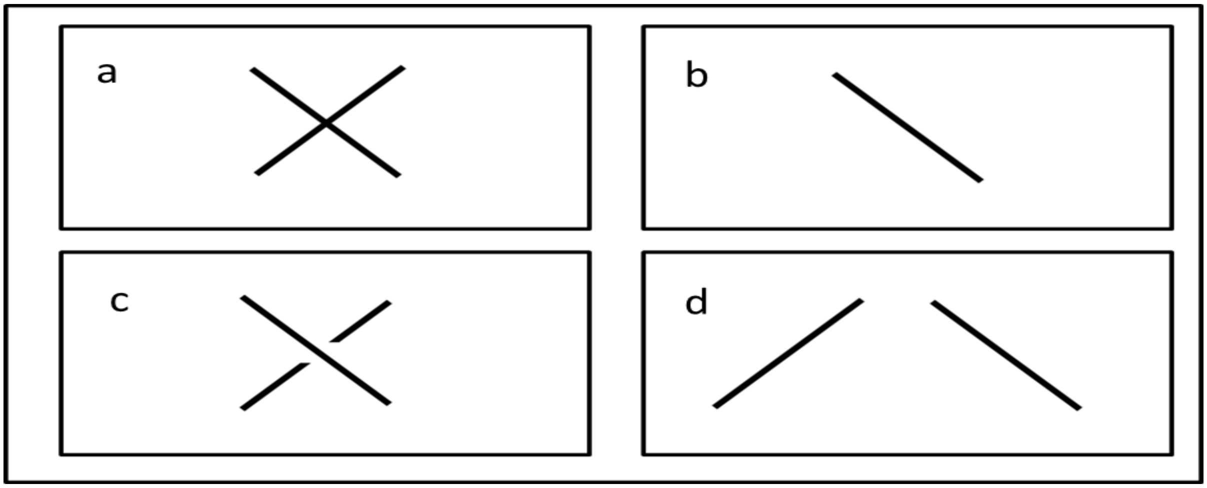


Figure 1-5: Perceived responses from BSGT

a) showing fusional response seen in normal retinal correspondence or anomalous retinal response, b) Right eye suppression, c) central suppression and d) diplopia (Image adapted from von Noorden, 2002).

1.3 Amblyopia

1.3.1 Definition and types

The term amblyopia literally means “dull vision” (ambly – dull). Von Graefe crudely defined it as *“the condition in which the observer sees nothing and the patient very little”*[56].

However it is scientifically defined as a "*decrease in visual acuity in one eye when caused by abnormal binocular interaction or occurring in one or both eyes as a result of pattern vision deprivation during immaturity, for which no cause can detected during the physical examination of the eyes and which in appropriate cases is reversible therapeutic measures* [56]. Amblyopia is classified into three groups based on the etiology; strabismic amblyopia, anisometropia amblyopia and visual deprivation (amblyopia ex anopsia)[11,21,56].

1.3.2 Amblyopia and Suppression

It should be noted that suppression plays a major role in the amblyopia. In other words, all amblyopes would have suppression but not vice versa. For example, alternating strabismics would have suppression to avoid diplopia or confusion. Since they have alternating fixation, they might not have amblyopia. There are two different schools of thought on amblyopia and suppression. The first school of thought suggests that suppression is a consequence of amblyopia. Indeed, Holopigian et al[20] showed a negative correlation between amblyopia and suppression, i.e. greater the amblyopia; the less suppression is needed to eliminate the binocular summation. The second school of thought suggests that amblyopia is a consequence of suppression. In this scenario, the suppression develops due to a disruption in binocular function (either because of strabismus or anisometropia). However, Li et al, 2011 [32] have measured the degree of suppression using global motion technique in 43 amblyopic (strabismic and anisometropic) patients and showed a positive correlation between amblyopia and suppression. They also have also argued that the results of Holopigian et al (1987) was because of their 10 participants, only of whom had visual acuity worse than 20/30 in the amblyopic eye.

1.4 Binocular integration:

Early work by Legge (1984) [30] suggested that binocular integration involves purely excitatory pathways (Figure 1-6 A) and followed by binocular summation. However, based on the findings of Baker (2007) [4 19], a new binocular vision model was proposed (figure 1-6 B). The model suggested that binocular vision involves inhibitory as well as excitatory signals before binocular summation. The main difference between the early Legge's model and the 'Two stage model' is that the first stage (before binocular summation) receives suppressive inputs from the other eye i.e. inter-ocular suppressive inputs. In normal participants, there is a balance between the excitatory and inhibitory signals, i.e. balance between the inter-ocular suppressive inputs. But, in amblyopia (figure 1-6 C), there is an imbalance in the inter-ocular suppressive inputs due to 1) signal attenuation and 2) additional multiplicative noise (G_{σ}) to the amblyopic eye (prior to binocular summation) and hence the inputs from each eye reaching the summation with greater weights from the fellow normal eye.

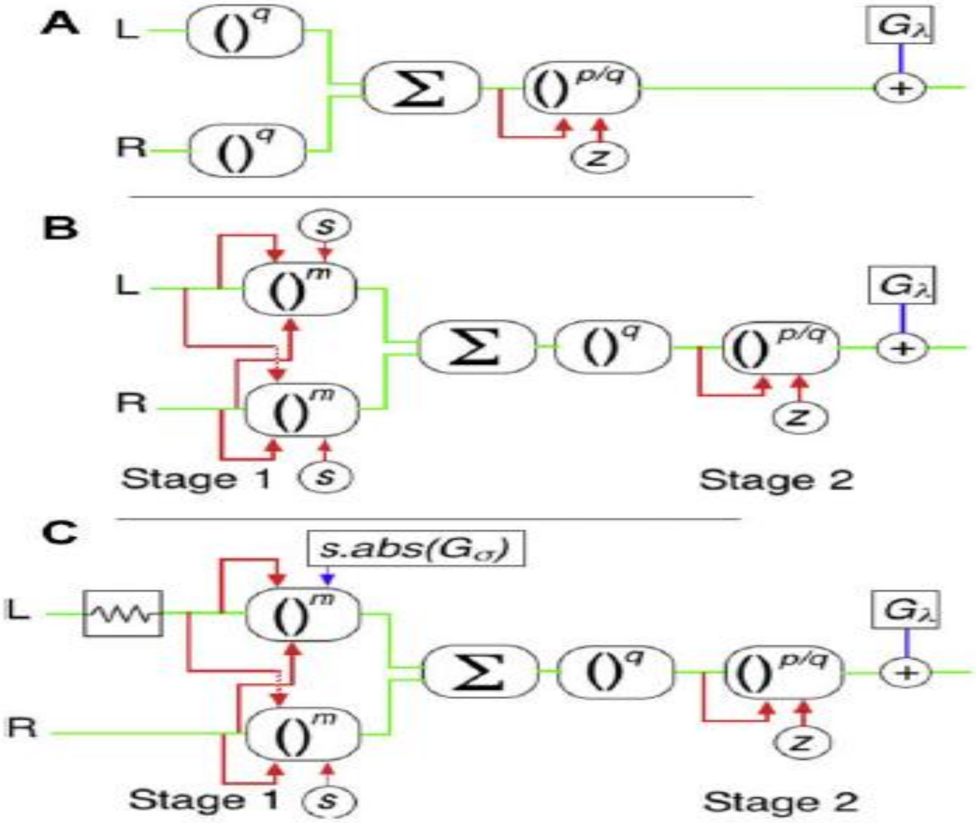


Figure 1-6: Models of binocular vision

A) Legge's model of binocular vision which shows just summation. B) Two stage of normal participants. C) Two stage model of amblyopes. p,q,m are excitatory components; G – noise generator; L – left eye; R – Right eye; Green lines represent excitatory signals and red lines represent inhibitory signals (Mansouri et al, 2008) [Copyright obtained – Appendix C].

Binocular summation:

The binocular summation ratio is the ratio of binocular to monocular sensitivities [4]. It is an indication of binocular advantage and is often measured using sine wave gratings [4,30]. This ratio for the normal observers will be around √2 (≈1.4), i.e. typically higher than summation of the two monocular signals [7]. If the ratio is unity, then there is no binocular advantage and this is the scenario in the amblyopic observers. Thus the amblyopic observers have lower binocular summation (near unity) at higher spatial frequencies which led to a conclusion that binocular summation of contrast is absent [42]. The reason for reduced/absent of binocular summation might be due to the loss of binocular cortical neurons. But recently a study done by Baker et al (2007)[4] suggested that in human amblyopes, the absence of binocular summation is due to the substantial difference between the monocular threshold of dominant and non-dominant eyes. They also added that binocular summation could be achieved by attenuating the signals to the normal eye, i.e. reducing the contrast of images to the dominant eye. But the question is how much of the contrast is to be reduced to the dominant eye in order to achieve binocular summation, i.e. how much of the contrast has to be reduced to achieve that balance point between two eyes. This balance point can be found be the technique called 'Motion Coherence threshold'.

Motion Coherence threshold (MCT):

A novel method has been developed to measure the depth of suppression using random dot kinematograms (RDK) [34]. This method has been developed on the basis of the new binocular vision model by Messe et al [38]. This involves estimation of global motion estimation under dichoptic setup using a method wherein the performance of each eye is to integrate signal seen through one eye and noise through the other eye. One hundred dots are displayed upon a mean luminance background of 35candela/meter^2. One eye was presented with 'signal' dots that all will move in a coherent direction (i.e. either right or left). The other eye was presented with 'noise' dots that all would move in random direction (Figure: 1-7). The task is to indicate the motion direction of the signal dots. Then the signal-noise ratio is calculated. The lowest number of signal dots required to detect the direction of the signal dots represents *'motion coherence threshold'* (MCT). The threshold would also be measured at 5 contrast offsets between the two eyes with signal is presented to the dominant eye or the non-dominant eye. The contrast ratio to the non-dominant eye is always fixed at 80-100% whereas the contrast ratio to the normal eye varies. Then the MCT of the dominant eye and the non-dominant eye would be plotted as a function of contrast ratios (figure: 1-8). Then the plots would be fitted linearly for the dominant eye and the non-dominant eye separately. The intersection of the two linear fits represents the *'balance point'*[34,58].

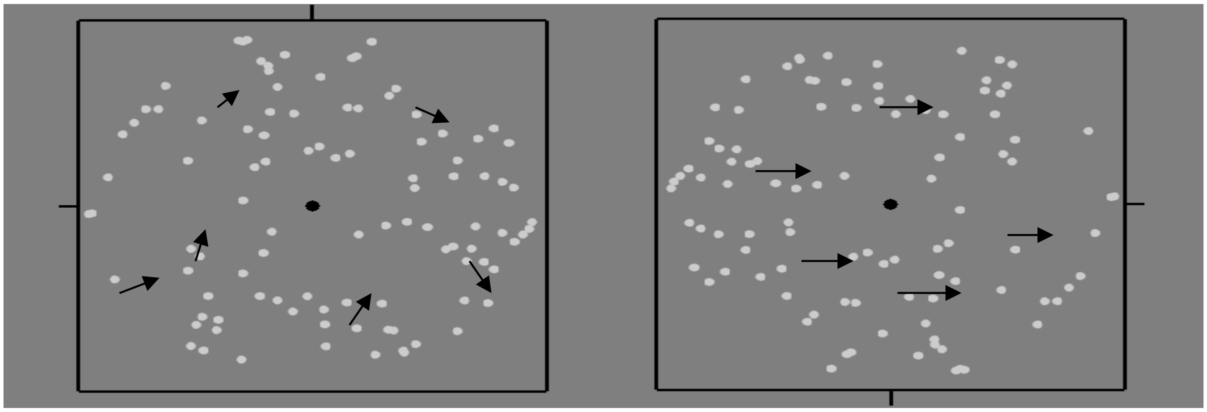


Figure 1-7: Random dot kinematograms (RDK).

One eye (Image on the right) seeing the signal dots (moving in a coherent direction) and the other eye seeing the noise dots (moving in random direction) (Zhang et al, 2011).

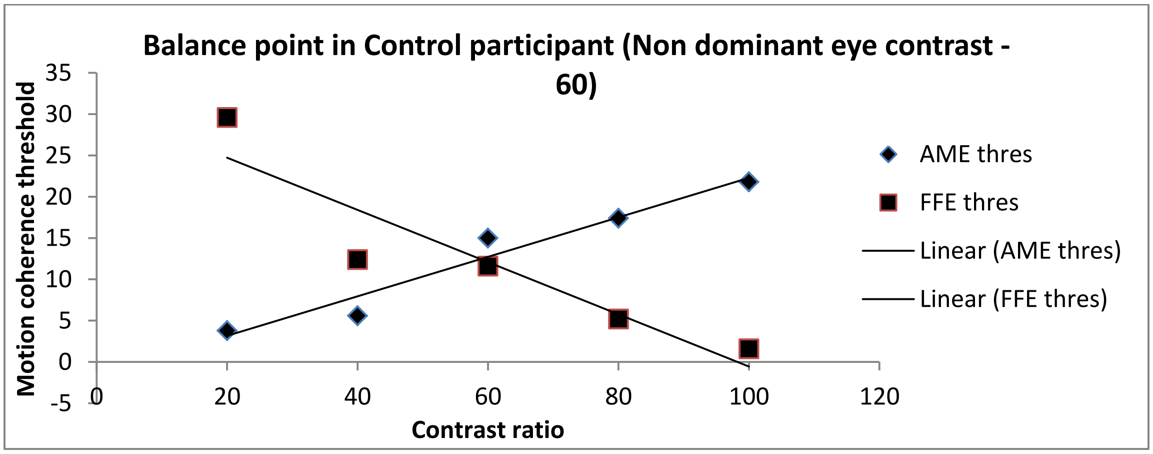


Figure 1-8: Balance point calculation.

The MCT of the dominant eye and the non-dominant eye was plotted as a function of contrast ratio. The intersection of the two linear fits represents balance point (Zhang et al 2011).

The balance point has a significant role in this thesis. This research thesis is about the eye movements in strabismics amblyopes, especially challenging their fixational eye movements and fusional vergence, once their strabismus is optically aligned and the interocular suppression is eliminated by attenuating the signal from the dominant eye.

Chapter 2: FIXATION EYE MOVEMENTS IN NORMALS AND AMBLYOPES

2.1 Introduction

Eye movements are of two main types: those that stabilize the image on the fovea (vestibular, visual fixation, optokinetic and smooth pursuit) and those that bring image on to the fovea (nystagmus quick phase, saccades and vergence) [31]. There are six types of extra ocular muscles which facilitate these eye movements: four rectus muscles (superior, inferior, medial and lateral) and two oblique muscles (superior and inferior) [26,56].

To see a stationery object best, image should be held on fovea. But it has been known since the 18th century that our eyes are never still even during fixation. The main goal of the oculomotor fixation eye movement is not just retinal image stabilization but also to prevent image from fading out (Troxler's effect) by optimal image motion [36]. There are three types of eye movements that occur during visual fixation: ocular tremors, drifts and microsaccades [9,11,36,37].

2.1.1 Fixation in normals:

Tremors:

Otherwise called as physiological nystagmus and defined as an "*aperiodic, wave like motion of the eyes with a frequency of approximately 90 Hz*" [36]. This is the smallest of all eye movements and is difficult to measure as the amplitude (0.01°) [31] of tremors is usually in the range of the recording system's noise [36]. The contribution of tremors in the maintenance of vision is not clear as the frequency of the tremors is much higher than flicker frequency threshold. Tremors are thought to be independent in the two eyes [36].

Ocular Drifts:

“Drifts are small and slow movements which occur simultaneously with tremors and take place between microsaccades” [36]. Drifts are thought to be random eye movements that are generated by instability of the oculomotor system. It could also be a restoring elastic force of extra ocular muscles which pulls away the eye from its position [36].

Microsaccades:

“*Microsaccades are involuntary jerk-like fixation eye movements that occur 3-4 times per second”* [36,37]. They are the largest and the fastest among all three fixational eye movements. They are typically less than a third of a degree and can be suppressed during visual tasks that demand steady fixation like threading a needle. The amplitude of microsaccades is not the only criterion to differentiate it from normal voluntary saccades, because the normal voluntary saccades can also be made to such small degrees [13,31]. Microsaccades are involuntary and occur only when the person attempts to fixate an object. Like normal voluntary saccades, the microsaccades do follow ‘main sequence’ [31]. The role of microsaccades in visual perception is not clear. However, recent studies suggested that the microsaccades increase the refresh rate to counteract receptor adaptation. On the contrary, there are studies which consider these fixational eye movements as random eye movements and not goal-directed[29,55]. Based on this, they developed a stochastic model on fixational eye movements[55].

The stability of fixation eye movements was first measured by Krauskopf, Riggs et al (1959)[27] and they showed that under monocular and binocular viewing conditions, these eye movements are very precise and variations are small, being less than 3’. Steinman et al (1982) [51] and Ott et al (1992) [41] have also measured the stability of fixational eye movements. Ott et al (1992)[41] have measured mean and standard deviation of binocular fixation eye movements to quantify the stability of fixation and he found; for horizontal fixation eye movement: 0.11°±0.05°, for vertical fixation: 0.15°±0.07°. Kruaskopf et al (1960) [27] have also measured correlation between the horizontal eye positions of two eyes. They sampled few eye position data without any microsaccades and found poor correlation. Hence they concluded that ocular drifts are uncorrelated and non-conjugate. Then, they sampled eye positions including microsaccades and found correlation coefficients to be around 0.34 to 0.52. Therefore they concluded that the microsaccades are the main source for correlation between two eyes.

2.1.2 Fixation eye movements in amblyopes:

Ciufredda et al (1979) [10] measured and evaluated fixational eye movements in strabismic and anisometropic amblyopes and qualitatively noted four abnormal patterns of eye movements during fixation; increased ocular drifts, saccadic intrusions latent nystagmus and manifest nystagmus. The average amplitude of the ocular drifts seen in the amblyopic eyes was 0.7 degrees (peak to peak drift amplitude even as high as 3.5 degrees) which is higher than the amplitudes of drifts seen in normal eyes. They have also found drifts accounting for 75% of the total fixation time in amblyopes without strabismus, 50% of the total fixation time in constant strabismic amblyopia and 20% of the total fixation time in intermittent strabismus. Hence they concluded that amblyopia (rather than strabismus) was the factor responsible for increased drifts (as drifts seen in the group of amblyopes for 75% of time). In amblyopes, saccadic intrusions mean amplitude was 0.7 degrees with a range of 0.25 – 5 degrees (saccadic intrusions are horizontal saccades which results in net change of the eye position). Saccadic overshooting (the primary saccade has larger amplitude than required) and glissadic undershooting (slow drifting eye movement) were also observed in amblyopes [10]. Similar to normal eyes, the saccades in the amblyopic eyes could be controlled during visual attention and fixating small targets. But the information of fixation stability was missing.

Stability of fixation eye movements in amblyopes:

Recently Gonzalez et al (2012)[13] have used the measure called Bivariate Contour ellipse area (BCEA) to quantify the stability of fixational eye movements. Gonzalez et al (2012) [13] quantified the stability of fixation in amblyopes and normal binocular vision participants. They calculated BCEA (bivariate contour ellipse area) to quantify the stability of fixation. The BCEA value represents region/area of fixation over which the eye positions are found for a 68.4% of the time and this value has been used to quantify stability of fixation (further details on calculation of BCEA are in methods section) [13,50,52–54]. The smaller BCEA value indicates better fixation stability. In normal participants, Gonzalez et al (2012)[13] found that fixation stability was better with binocular viewing compared with monocular viewing. In amblyopes, they found poor fixation stability with amblyopic eye viewing and also relatively poorer fixation stability with binocular viewing than found in normal participants. Hence, concluded that binocular summation has bigger role in fixation stability.

Interestingly, it has been established that oculomotor aspects get normalized after successful amblyopia therapy. Ciufredda et al (1979) showed that eye movement aspects like ocular drifts amplitude, glissadic undershoots, steady fixation and pursuit gain get normalized after successful amblyopia treatment[10]. However, some oculomotor aspects do not become normalized; these functions include saccadic latency and saccadic overshooting. But all of his findings were on only one subject who showed stereopsis improved from 800 arc seconds to 60 arc seconds and visual acuity to 6/6. It is important to distinguish a monocular improvement in visual acuity from binocular integration. In the case of strabismus the latter may never be achieved in all cases. While in the case of anisometropic amblyopia binocular vision can be restored but typically well after the amelioration of amblyopia.

Chapter 3: OBJECTIVE OF THE STUDY

Many novel anti-suppression therapies like balanced contrast techniques [18] have evolved which attempt to improve binocular functions like stereopsis. This is unlike traditional patching therapy where monocular function like visual acuity is targeted. They have also noted significant improvement in visual acuity of the amblyopic eye and also notable improvement in stereopsis when the suppression is reduced with balanced contrast between the normal eye and the amblyopic eye (i.e. with binocular summation). But little is known about the effect of the aforementioned ‘balance point’ on oculomotor aspects.

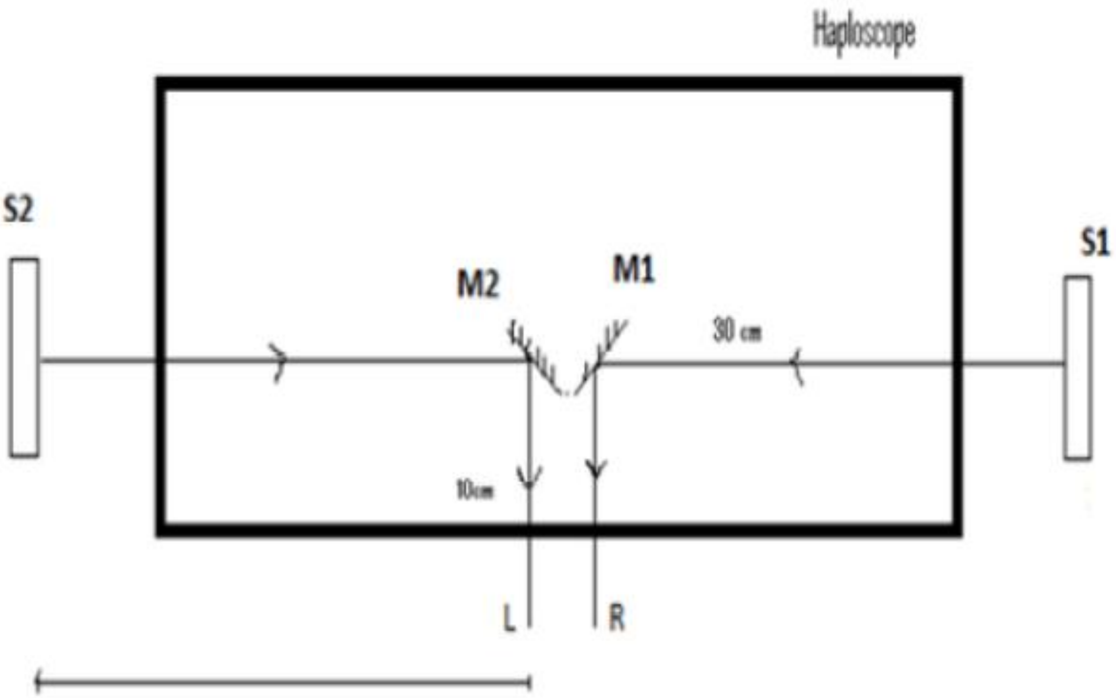
It has been well established that oculomotor functions like visual fixation and disparity vergence in the amblyopes are poor [5,9,13,25]. They have all listed that lack of binocular summation or loss of binocularity due to foveal suppression as the reasons for poor oculomotor control. But it is unclear what underlying mechanism (sensory or motor aspects) is responsible for producing such abnormal movements. It is also unclear whether the lack of foveal stimulation or lack of binocular summation is causing this poor fixation stability and this study will try to address all of these research questions. Hence we hypothesize that the stability of fixation should improve if we align the strabismus (i.e. bi foveal stimulation) and eliminate the inter-ocular suppression (reducing the contrast to the fellow fixing eye, thereby facilitating balanced monocular inputs).

Chapter 4: INSTRUMENTATION AND METHOD

To test our hypothesis, we had to consider three things: 1) optical alignment of the angle of strabismus, 2) elimination of inter-ocular suppression in the strabismic patient and 3) measurement of resulting eye movements.

4.1 Ocular Alignment

A haploscope was designed to optically align the eyes while strabismic subjects dichoptically viewed two similar targets imaged onto two LCD monitors (9”Lilliput®) which were placed at the distal end of each haploscope arm. The participants viewed the monitors through two front-surface mirrors (2” x 3”) placed orthogonally at 10cm from the lateral canthus and 30 cm from the monitors. Thus, the total optical length was 40 cm for each arm. (Figure: 4-1a and 4-1b). Chin and forehead rests was clamped at 10 cm from the mirrors. To stabilize head movement, the participant’s head was strapped along with forehead rest using Velcro strap. Two monitors on the haploscope were controlled by a MacIntosh laptop and resolution of the secondary monitors (haploscope monitors) was set to 1600x600 pixels. Using an external multi-display adapter (DualHead2Go, Matrox®), the resolution of the secondary monitors was split into two such that each monitor shared 800x600 pixels resolution. The gamma correction for our haploscope monitors was found to be 2.2. See the Appendix-I for more details.



M1 and M2 - front surface mirrors, S1 and S2 - LCD monitors, L and R - left and right eye and its tracker. Mirror to eye distance - 10 cm and Mirror to screen distance 30 cm.

Figure 4-1: Schematic and actual picture of the haploscopic setup

As mentioned before, the main purpose of the haploscope is to optically align the strabismic patients. The reason for using haploscope over a prismatic correction is that 1) dichoptic setup (information from each eye can be evaluated better) and 2) attenuation of the signal to the normal eye can be done efficiently (i.e. contrast to the fellow fixing eye can be reduced easily).

4.1.1 Calibration of the haploscope

The angular scale of the haploscope needed to be calibrated for actual eye movements as the centers of rotation of the haploscope arms do not coincide with the center of rotation of the eyes. Dissimilar targets, a big white circle on a black background in one screen and a small black circle on a white background, were used in order to avoid the influence of fusional vergence (Figure: 4-2). A known amount of ophthalmic prism (15Δ - 45Δ base out) was placed in front of one of the eyes so that it would induce saccadic eye movement (since it is a dissimilar object, fusional vergence would not be induced) by displacing one of the images. Then the arm of the haploscope was rotated until the participant reported that the images overlapped. The degree of rotation was noted and then the same procedure was repeated for other prisms. Six normal participants volunteered for this calibration process.

The results showed that the empirical values (haploscope rotation) are always higher than the calculated values (actual eye rotation). The variation in the results could be due to the inter-participant difference in the mirror-to-eye distance. The results were shown in the Table 4-1 and in the figure: 4-3.

Prism given	Corresponding Degrees (Calculated)	Degree of rotation in the haploscope (Empirical)					
		Participant 1	*Participant 2*	*Participant 3*	*Participant 4*	*Participant 5*	*Participant 6*
25	14.0	15.00	14.33	11.33	19.33	16	15
30	16.7	18.33	16.83	14.50	24.17	18	18
35	19.3	19.83	19.17	19.17	28.33	21.5	21.5
40	21.8	23.67	22.33	22.17	29.67	24	24
45	24.2	25.50	25.33	29.67	31.33	29	26

Table 4-1: Values of the calculated and the empirical values of eye rotation.

The values clearly show us that the empirical values (haploscope rotation) are always higher than the calculated values (actual eye rotation). The calculated values were determined according to the power of the ophthalmic prisms, e.g. 25Δ would shift the image such that the eye would rotate ~14°.

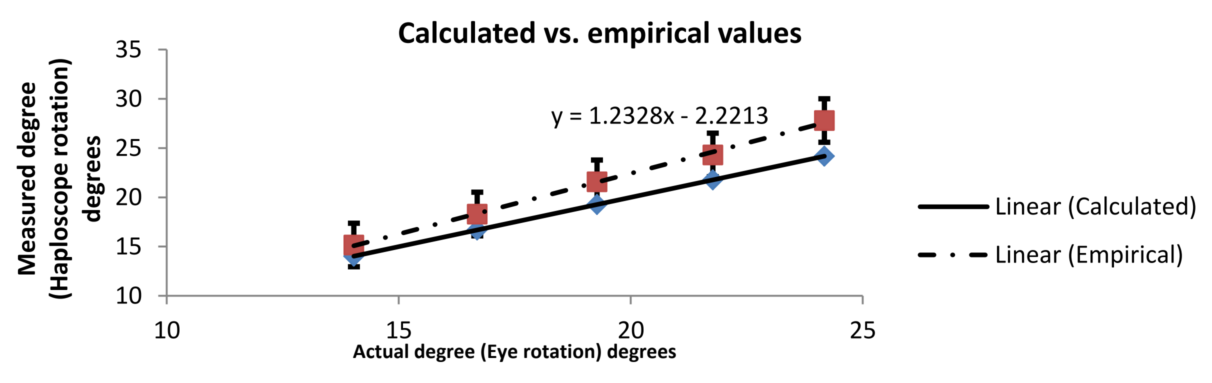


Figure 4-2: Empirical (measured eye rotation) values as a function of calculated values (actual eye rotation) Error bars represent 1 SD.

Figure 4-3: Dissimilar target used for the calibration of haploscope.

A big white circle on black background (right eye) and a small black circle on a white background (left eye).

Conclusion:

The results of this calibration have suggested that the arms of the haploscope should be rotated 1.2x times the degree to induce the required degree of eye movement. In other words, if we rotate the arm of the haploscope 5 degrees (according to the haploscope's scale) then it would induce approximately 3.5° ocular rotation only. However, the ocular alignment could be done efficiently using this haploscope. By doing alternating cover test while aligning the objective angle of the strabismus, we could make sure that the targets were bi-foveally fixated.

4.2 Attenuating inter-ocular suppression:

As explained in the previous chapter, binocular summation could be achieved in amblyopes if the contrast of the image to the fellow fixing (normal) eye was attenuated. A stimulus was designed (figure: 4-4).

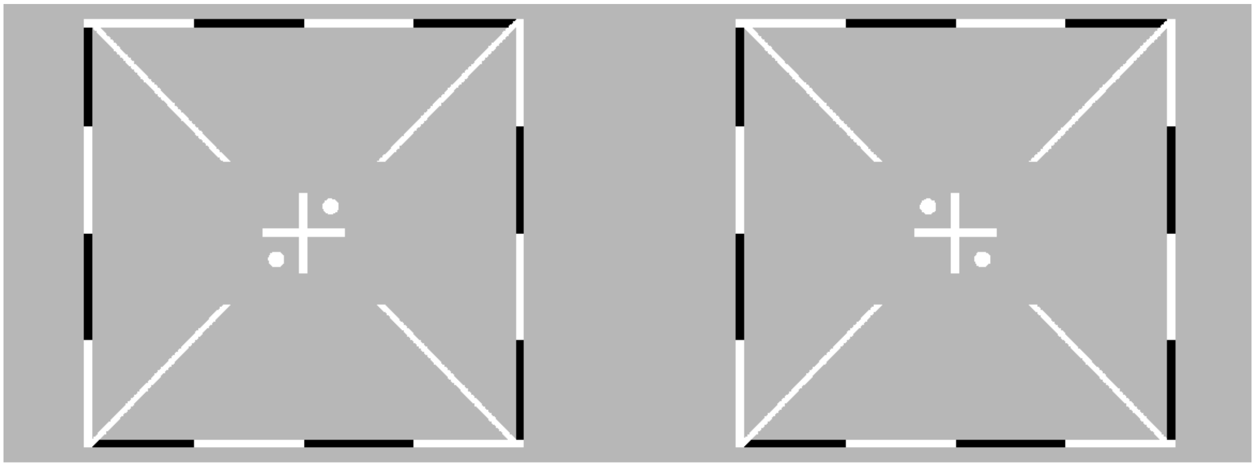


Figure 4-4: Stimulus for fixational and vergence eye movments.

Each target (box) shown to the each eye and when a participant fuses the images, it will appear as a single outer box with a single cross in the middle with four dots. The dots were to check suppression during the trial.

4.2.1 Description of the stimuli:

The stimulus was created using the software, Psychtoolbox, MATLAB (Mathworks, Inc. ®)[44][Dr. Jiawei Zhou, McGill University, QU, Canada, Personal communication, 29th Mar, 2012]. The stimulus had outer box which subtended 11.3° visual angle at 40 cm whereas the middle cross subtended 2.3° visual angle at 40 cm. Under dichoptic setup, each eye would see only two dots and these dots were used as suppression checks. So if a participant fused the stimulus (under dichoptic setup); he/she should see a single outer box with a single cross in the middle with four dots. The stimulus was shown on a gray background so that the contrast of the outer box, the cross and the dots could be varied on either side, i.e. increase/decrease the contrast easily using Weber's contrast[43].

4.2.2 Reducing contrast of the stimulus to the fellow fixing (normal) eye:

Contrast was defined as the Weber ratio of the difference between luminance of the feature and background to the luminance of the background (Equation-1) [43].

$$Weber's\ contrast = \frac{I - I_b}{I_b}$$

I – luminance of the feature and I_b – luminance of the features (here, the outer box, the cross and the dots). Weber's contrast is usually preferred over Michelson contrast in the cases where the small features are presented over the uniform background. In the code (Matlab) (Appendix-C), the luminance was defined as the scale of 0 to 1, where 0 is black and 1 is white. The background was set gray i.e. 0.5 in the luminance scale. For example, in order to set the contrast of the image to 20% (i.e. reducing 90%), the value of 'I' should be 0.1 and 'I_b' should be as always 0.5. Substituting these values in the above equation would set the contrast of the image at 20% (For detailed description of Weber's contrast and calculation, please refer Appendix-B).

4.3 Measuring eye movements:

A binocular infra-red eyetracker *(ViewPoint EyeTracker® PC-60, Arrington Research Scottsdale, USA)* was used to track the eye movements. Eye movements were sampled at the rate of 60Hz (High Speed Wide mode) which has been shown to be sufficient for measuring vergence eye movements [45]. The specifications of the eyetracker are summarized in the table 4-2. The eyetracker was mounted on a spectacle frame as shown in the figure: 4-5. The spectacle frame was big enough to fit over participant's own prescription glasses.

Parameters	Specification
Eye tracker type	Video based infrared eye tracker
Tracking method	Dark pupil method
Sampling frequency	60Hz (High Speed Wide mode)
Range of measurement	Horizontal: ±44°
	Vertical: ±20°
Spatial resolution	0.15°
Accuracy (as noted in the user manual)	0.25° - 1°

Table 4-2: Specification of the eyetracker

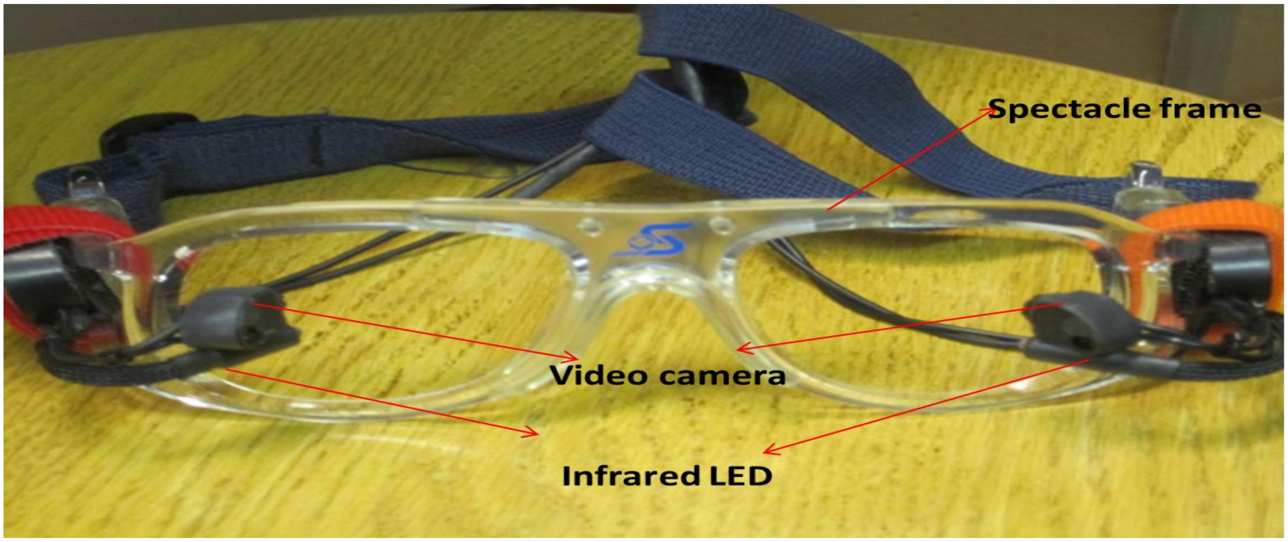


Figure 4-5: Eyetracker mounted on a spectacle frame.

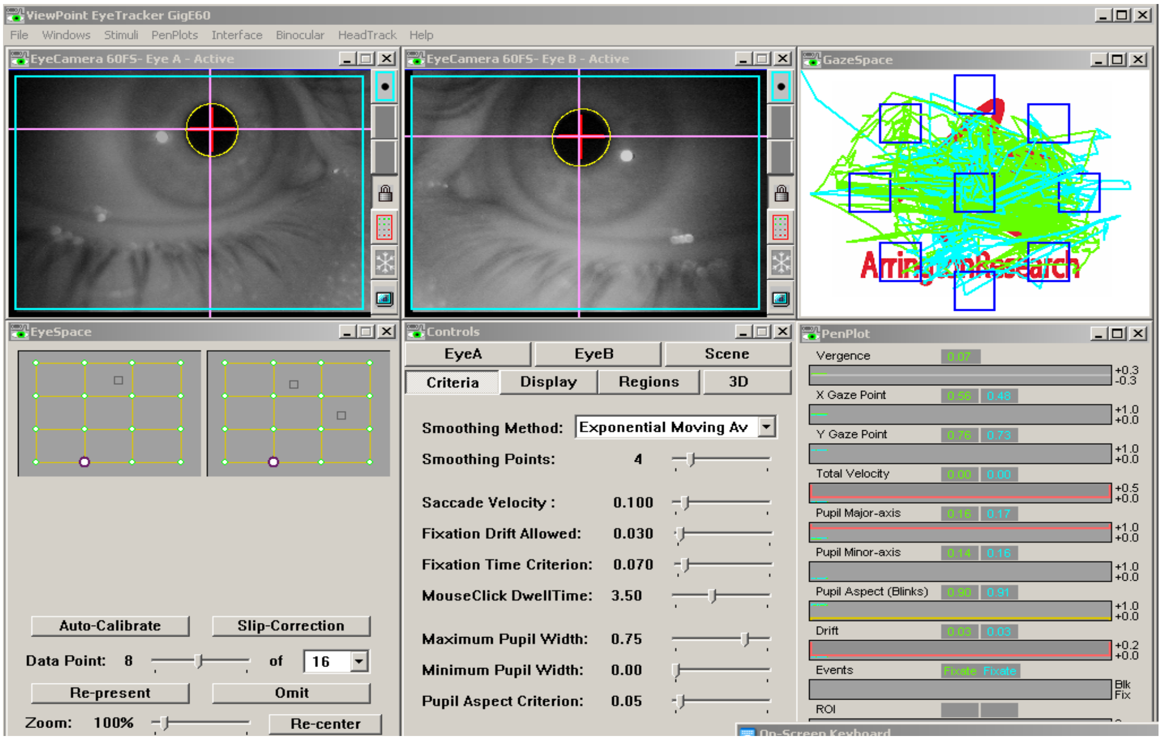
Eye movements data were collected using software Viewpoint®, Arrington Research and analyzed using software called 'ILab' [12]. This is free software and available online (http://www.brain.northwestern.edu/ilab) which was created by Dr. Darren Gitelman, Northwestern University Medical School, Chicago, Illinois.

4.3.1 Setting up Eyetracker to measure eye movements:

To measure eye movements, the eye tracker parameters were adjusted according to our instrumental setup. The information like total viewing distance (here, 40cm) and resolution of the stimulus window (Haploscope monitor resolution, 1600x600) were entered in the software. After entering this required information, the participant was asked to wear the eyetracker and the care was taken to make sure that the eye tracker was positioned firmly without sliding down. If required, a sponge was used to provide extra support to hold the eyetracker firmly. Then the camera and the IR LED of each eye were adjusted such that pupil of the eye was tracked properly as shown in the figure: 4-6. Then the participant was asked to place his/her chin on the chin rest and asked to keep the forehead firm against the forehead head rest. At this position, the participant head was strapped along with the chinrest to minimize the head movement during the experiment.

4.3.2 Calibration of the eye tracker:

Calibration of the eyetracker was done by measuring the eye position at the predetermined 16 points in the stimulus window (i.e. Haploscope monitor screen). The calibration stimulus is shrinking motion of green rectangular frames (figure: 4-7) which appear randomly in the sixteen predetermined points. A good calibration is checked by looking at the arrangement of calibration point and is indicated by a relatively rectilinear and well separated configuration dots as shown in the figure: 4-7.



Data Point: 8 of 16

Zoom: 100%

Smoothing Method: Exponential Moving Av

Smoothing Points: 4

Saccade Velocity : 0.100

Fixation Drift Allowed: 0.030

Fixation Time Criterion: 0.070

MouseClick DwellTime: 3.50

Maximum Pupil Width: 0.75

Minimum Pupil Width: 0.00

Pupil Aspect Criterion: 0.05

Figure 4-6: interface of software Viewpoint®.

The top left (Eye camera window) is the picture of eyes getting illuminated by IR LED (dark pupil method). Eye A represents right eye and Eye B represents left eye. The top right is the stimulus window for user reference. The bottom right is the pen plot window where real-time vergence, x and y gaze points, velocity are seen. The left bottom is the calibration window where the settings of the calibration and calibration check can be seen.

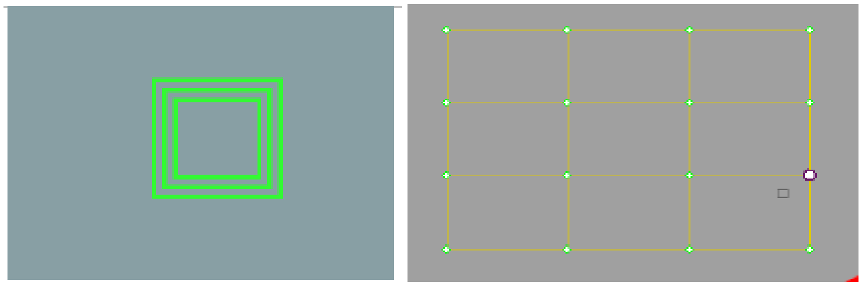


Figure 4-7: Stimulus for calibration of eye tracker.

a) (Left image) shows the calibration stimulus shrinking green square frames and b) shows a calibration points which are well spaced and relatively rectilinear indicating good calibration.

4.4 Participant selection:

Seven strabismic participants [5 esotropes and 2 exotropes] [Mean age: 29.17±9.47 years] [Mean visual acuity: AME = 0.39±0.13; FFE = -0.13±0.04] were recruited from the School of Optometry Clinic, University of Waterloo and informed consent was obtained from each participant. Relevant clinical details like visual acuity, sensory status (Worth's four dot test, Bagolini striated glass test and Random dot stereogram) and motor status (cover test and prism bar cover test) were collected. The details are tabulated in the table-1. Then the motion coherence test (Zhang, 2011)[58] was performed to measure balance point contrast ratio. However the contrast was fixed finally at the level where the participant had subjective response of constant fusion. It should be noted that all of our strabismic participants had central suppression with the Bagolini striated glass test (BSGT). In the case, if they had any form of ARC, then they would have experienced diplopia when they were aligned to their objective angle. Hence, the main inclusion criterion was that the strabismics should have at least central suppression with BSGT such that they would not experience any diplopia when their objective angle of strabismus was corrected and a balance point could be empirically measured. One participant (ON) was then excluded from the study, as a balance point could not be established since the participant could not perform motion coherence test nor subjectively respond well for contrast changes between FFE and AME. The remaining six subjects were included in the study.

Fixational eye movements were then measured in four different conditions; 1) **Unaligned/high contrast** [*strabismus unaligned and at 100% contrast target to both eyes (i.e. no bi-foveal stimulation and no binocular summation)*], 2) **Unaligned/balance point** *[strabismus unaligned but with balance point contrast (i.e. no bi-foveal stimulation but binocular summation)]*, 3) **Aligned/high contrast** *[objective angle of strabismus aligned but at 100% contrast target to both eyes (i.e. bi-foveal stimulation but no binocular summation)]* and 4) **Aligned/balance point** *[objective angle of strabismus aligned and balance point contrast target (i.e. bi-foveal stimulation and binocular summation)]*.

		Balanced Input	
		No	Yes
Bi-Foveal stimulation	No	Strabismus – unaligned Contrast – 100% target contrast to both eyes	Strabismus – unaligned Contrast – 100% target contrast to the amblyopic eye and reduced contrast to the normal eye
	Yes	Strabismus –aligned to objective angle Contrast – 100% target contrast to both eyes	Strabismus –aligned to objective angle Contrast – 100% target contrast to the amblyopic eye and reduced contrast to the normal eye

Figure 4-8: Four different viewing conditions used to measure fixational stability.

Ocular alignment for subject angles was achieved by applying the principles of the Douse Target Test used in synoptophore testing of strabismics. The subject's head was placed in the synoptophore. Each eye dichoptically viewed a cross which was displayed on both screens. An alternate cover test was performed in order to assess the direction of the strabismic angle. One arm of the haploscope was adjusted in order to reduce the deviation.

Using a method of limits a point was reached when there was no movement seen in the cover test. The subject then identified if the crosses where superimposed. If not, ARC was suspected and the subject reset the arms in order to note the angle of ARC. In cases however, testing commenced from the objective angle of the strabismus i.e. that determined by neutralization of the cover test. Then, the eye tracker was calibrated as described above and the eye movements were measured while the participants fixated each dichoptic targets for continuous 5 minutes. The target was as shown in the Figure: 4-2. The subjective response of each participant was noted in every condition to know the sensory status with particular condition (by asking *'how many dots and crosses are visible'*) so that we would know whether they had either suppression or fusion. These procedures were repeated for every strabismic participant but the orders of the above mentioned conditions (Figure: 4-1) were randomized for each participant.

For normal participants [Mean age: 25.3±4 years] [Mean Visual acuity: -0.1±0.08], the haploscope arm was rotated to certain degree where accommodation and vergence lie in the same plane, i.e. vergence demand for 40 cm according to their inter-pupillary distance. Once calibration of the eye tracker is done, the fixation eye movements were measured for 30 seconds in three conditions which was more likely representing strabismus participants; 1) right eye viewing the target and the left eye viewing no target, 2) left eye viewing the target and the right eye viewing no target and 3) binocular viewing. Then the results of both groups were compared.

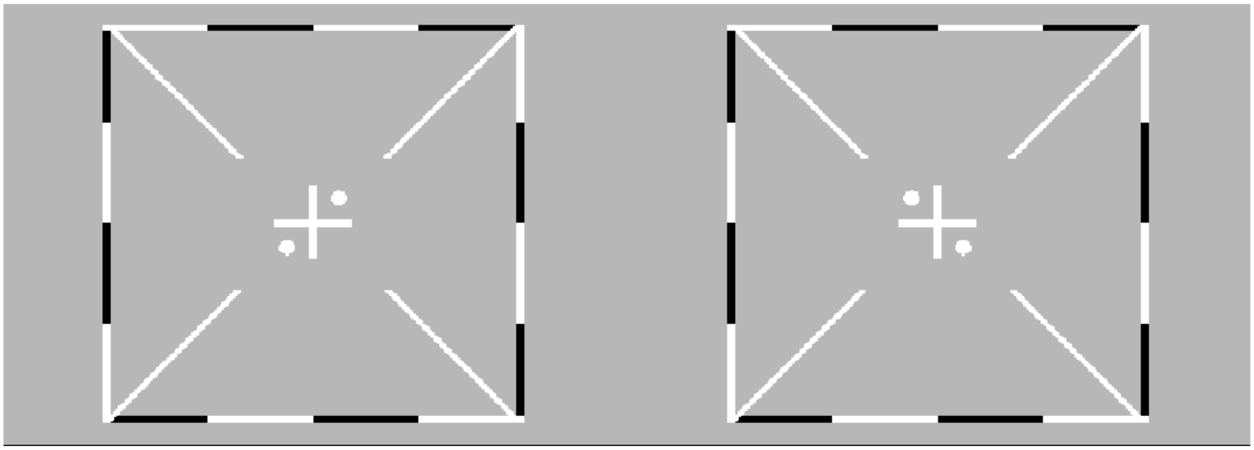


Figure 4-9: Target for the participants (normals and strabismics) to fixate with equal contrast to both eyes.

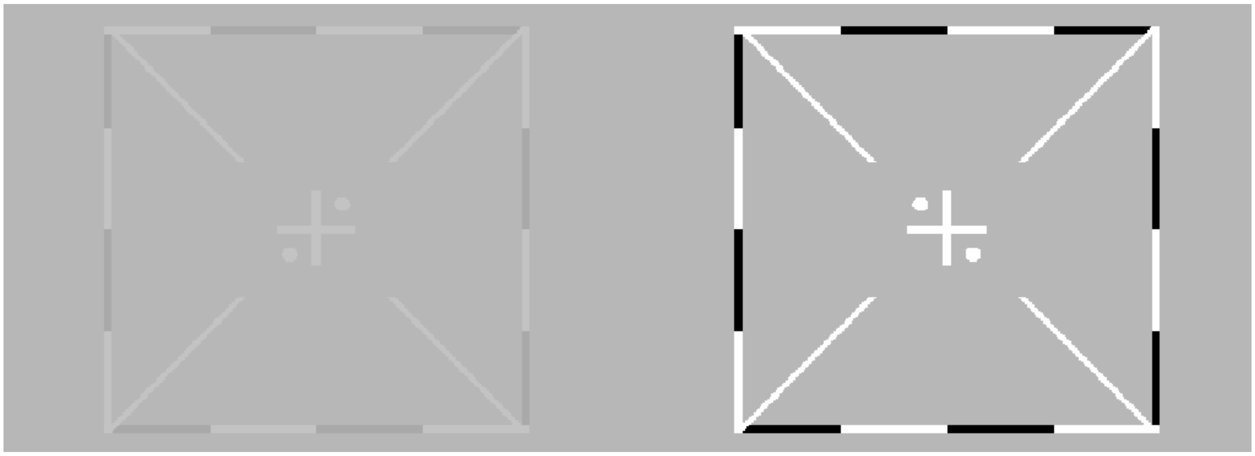


Figure 4-10: Target for the strabismic participants to fixate with balanced (reduced) contrast to the fellow eye

Analysis of data:

The collected data were analyzed using the software called ‘Ilab’. It was used to convert eye positions from screen coordinates (from Viewpoint) to degrees and also to remove blinks. The blinks were removed based on the criterion of axis limits, i.e. the coordinates were already set according to the resolution of the haploscope monitors

(1600x600); if the eye position exceeds these axis limits, then it was considered as a blink and removed from the data. Five data points were also deleted pre and post blink. Once the blinks were deleted, the horizontal and vertical eye positions were converted from screen coordinates to degrees and exported to MS Excel. Then the eye positions of each eye were plotted as a function of time. Stability of fixation eye movement was then measured for each eye by calculating global BCEA.

Fixational stability:

The measure of global BCEA (bivariate contour ellipse area) was used to measure the stability of fixation in normal and strabismus participants. The BCEA value represents the region/area of fixation over which the eye positions are found for a 68.2% of the time and it is calculated using the following equation,

$$\boldsymbol{BCEA = \pi\chi^2\sigma_x\sigma_y\ \ \overline{1-\rho^2}}$$

where σ_x and σ_y are standard deviation of the horizontal and vertical eye position, ρ is the Pearson’s correlation between the horizontal and the vertical eye positions during the trial and $\chi^2 = 2.291$ is the chi-square value (2 degree of freedom) corresponding to a probability value of 0.682(i.e.±1SD). **The smaller BCEA value indicates better fixation stability**. The BCEA values were transformed into log values to get normality.

Participant	Refraction	Visual acuity		Sensory status			Strabismus		Amblyopic eye
		OD	**OS**	**WFDT**	**BSGT**	**Stereopsis**	**D**	**N**	
XU 41/M	OD:+6.75/-2.50x30 OS:+5.00/-1.75x162	0.42	-0.08	D: Intermittent suppression N: Fusion	Central Suppression (OD)	No gross stereopsis	10 PD RET	12 PD RET	OD
MA 27/M	OD:+2.50/-1.25x20 OS: plano	0.54	-0.14	D: Uncrossed Diplopia N: Fusion	Central Suppression (OD)	No gross stereopsis	8 PD RET	14 PD RET	OD
ON 20/F	OD:+0.50 OS:+4.50/-1.00x35	-0.12	0.2	D & N: Fusion	Central Suppression (OS)	No gross stereopsis	8 PD LET	12 PD LET	OS
OT 22/M	OD:-1.00 OS:-1.00/-0.25x160	-0.1	0.34	D & N: Fusion	Central Suppression (OS)	200 arc sec	4 PD LET	4 PD LET	OS
ST 24/F	OD:-2.75/-0.75x25 OS:-3.25/-1.25x10	0.52	-0.12	D & N: Fusion	Central suppression (OD)	200 arc sec	6 PD RXT	6 PD RXT	OD
MT 42/M	OD:-2.75/-1.00x105 OS: -2.75/-1.00x80	0.34	-0.2	D: Intermittent suppression N: Fusion	Central suppression (OD)	No gross stereopsis	6 PD RET	8 PD RET	OD
AD 40/M	OD:-1.00 OS: plano	1.12	-0.1	OD: Suppression	OD: Suppression	No gross stereopsis	6 PD RXT	6 PD RXT	OD

Table 4-3: Details of sensory and motor status of the participants

Abbreviations used: WFDT – Worth four dot test, BGST – Bagolini striated glass test, D – Distance, N – Near, PD – prism dioptres, RET – Esotropia, LET – Left esotropia, RXT – Right exotropia

Chapter 5: RESULTS

5.1 Qualitative analysis of fixation pattern:

5.1.1 Fixation pattern in normals:

As noted earlier, the stability of fixation was measured under three different conditions. In the monocular condition, fixation was more stable in the eye which was viewing the target than the covered eye (Fig: 5-1). Under binocular conditions, both eyes had same pattern of visual fixation (Fig: 5-2).

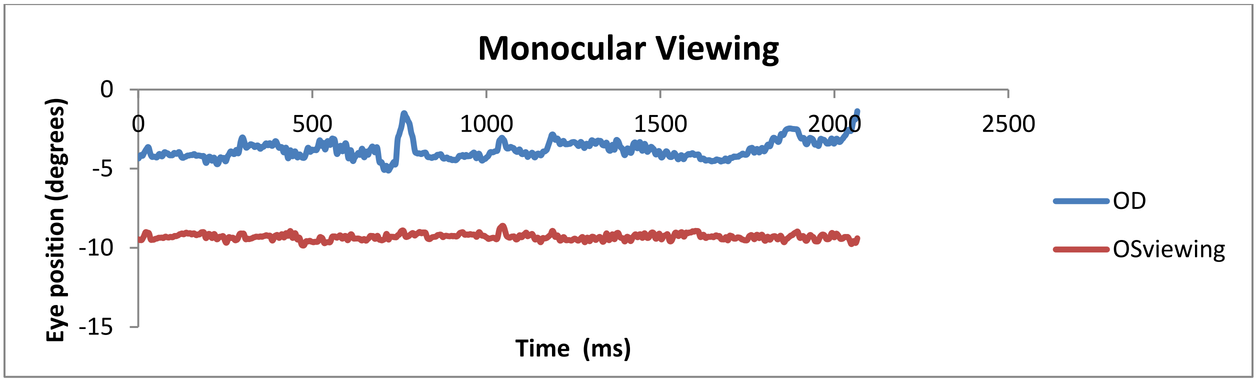


Figure 5-1: Monocular viewing eye trace of normal participant

Blue line and red line represents right eye and left eye respectively. OD was viewing the monitor covered with black sheet of paper whereas the OS was viewing the target. These eye traces show the non-viewing eye (here OD) with poor fixation.

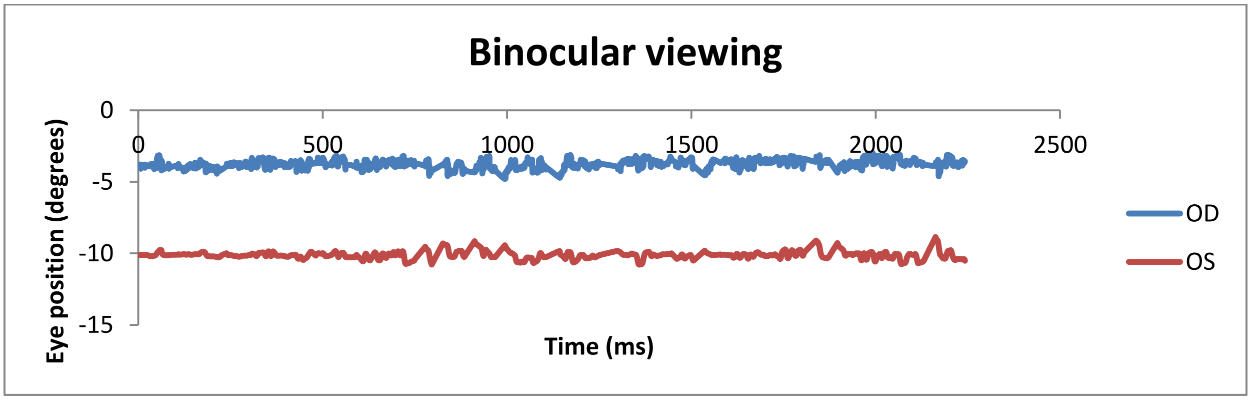
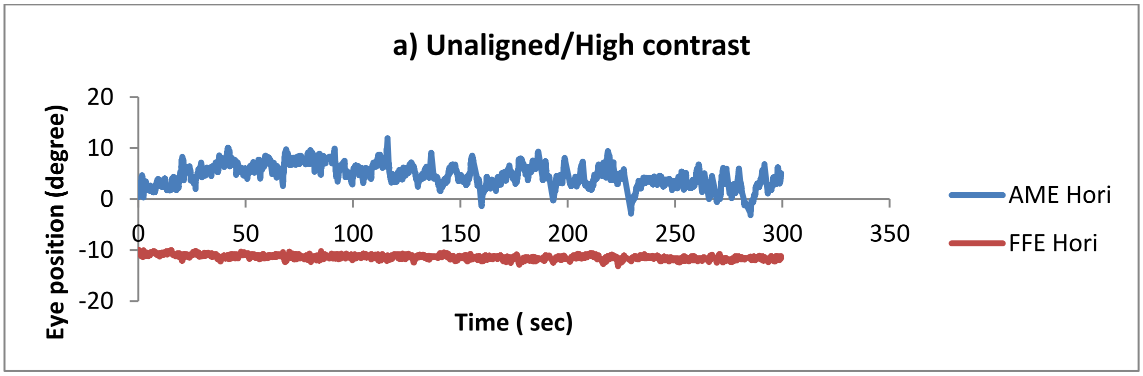


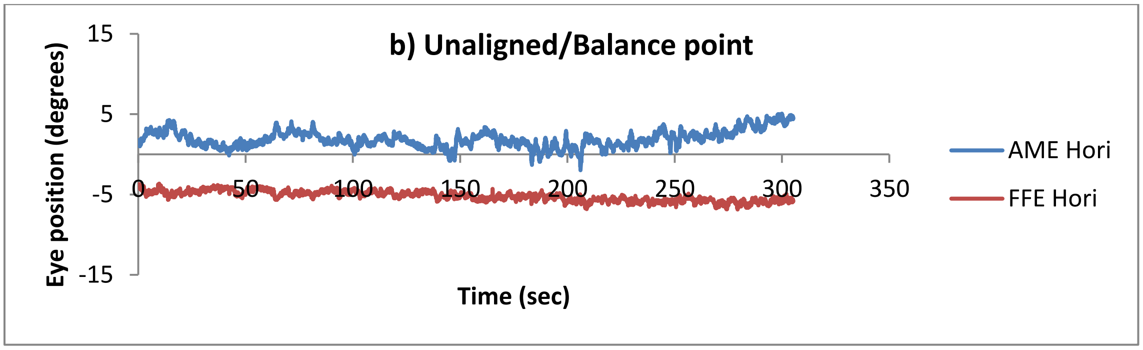
Figure 5-2: Binocular viewing eye trace of normal participant

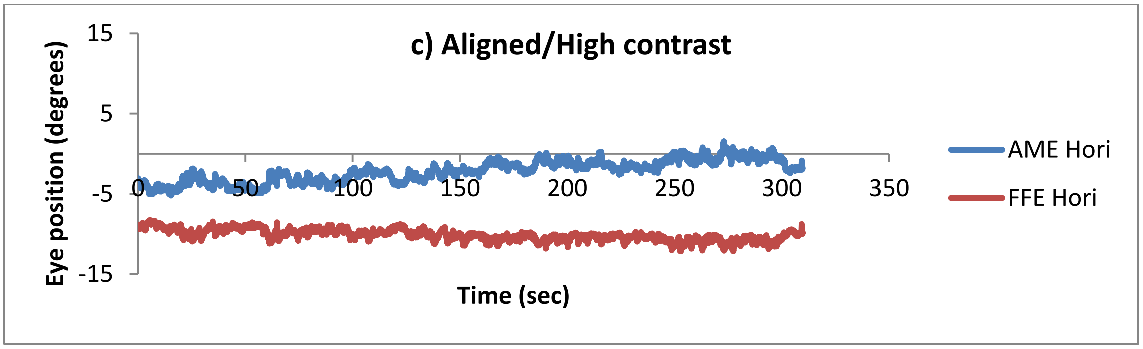
Traces of horizontal eye position of a normal participant while both eyes viewed the target. Blue line and red line represents right eye and left eye respectively. Fixation of both eyes appeared to be as stable as that of the viewing eye in monocular condition (p=0.99)

5.1.2 Fixation patterns in strabismic amblyopes:

The eye movement traces of two (XU and ON) of the six strabismic participants under four different conditions are shown in the Fig: 5-3 and Fig: 5-4. The traces have suggested that in an unaligned position, the fellow fixing eye (FFE) was holding fixation whereas the amblyopic eye (AME) showed poor fixation with higher amplitude of drifts. But the fixation was improved when the objective angle of strabismus was aligned i.e. bifoveal fixation. The fixation was even better when the strabismus was aligned and also when the contrast was balanced between FFE and AME.







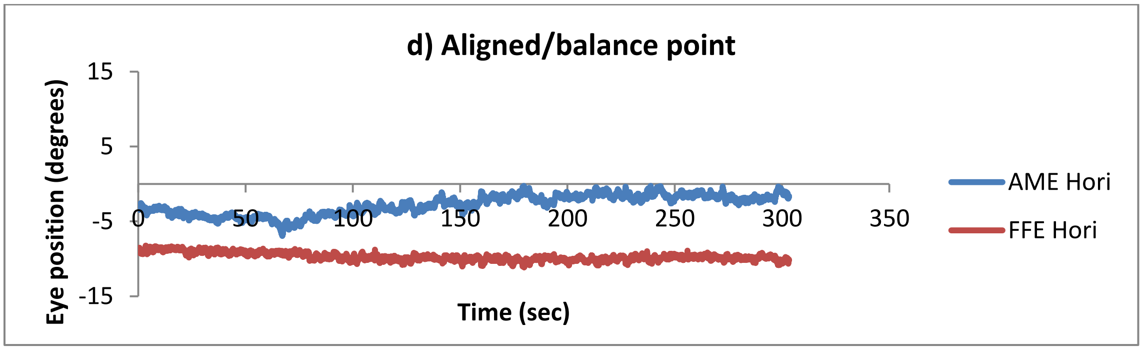
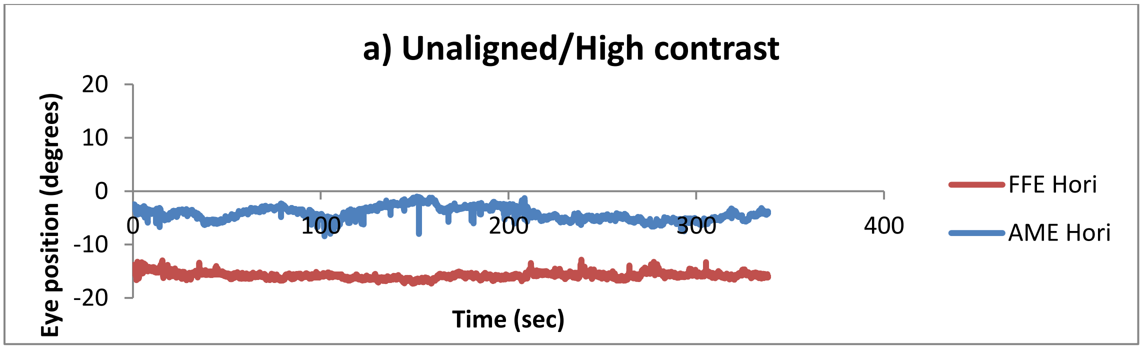


Figure 5-3: Fixation eye trace of the participant XU.

The traces show the horizontal eye position of the amblyopic eye (AME) and the fellow fixing eye (FFE) over the first 5 minutes of viewing. The conditions are listed as follows (from top to bottom): Unaligned/high contrast, Unaligned/balance point contrast, Aligned/high contrast and Aligned/balance point. Blue lines represent eye traces of the amblyopic eye (AME) and brown lines represent eye traces of the fellow normal eye (FFE). The eye traces show that the quality of fixation was poorer at the unaligned position with greater amplitude of drifts. However, these drifts were reduced and the quality of fixation improved with the alignment of the eyes and balance point. In the condition of aligned/balance point, however, the achieved optimal fixation was very transient. After initial period of optimal fixation, higher amplitudes of drifts were seen.



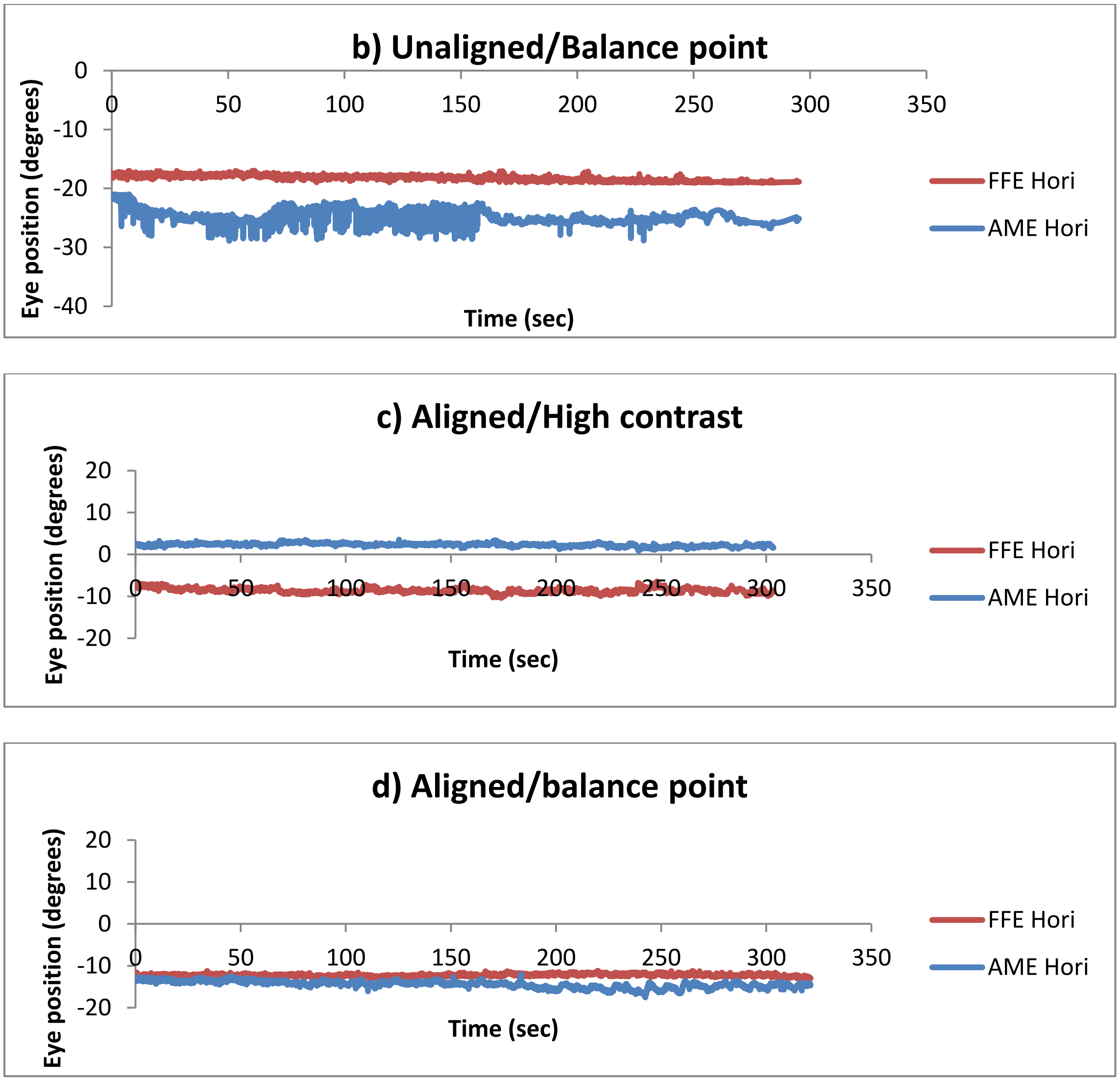


Figure 5-4: Fixation eye trace of the participant (OT)

The conditions are listed as follows (from top to bottom): Unaligned/high contrast, Unaligned/balance point contrast, Aligned/high contrast and Aligned/balance point. Blue lines represent eye traces of the amblyopic eye (AME) and brown lines represent eye traces of the fellow normal eye (FFE). The eye traces have shown that the quality of fixation was poorer at the unaligned position with greater amplitude of drifts. However, these drifts were reduced and the quality of fixation improved with the alignment of the eyes and balance point. In the condition of aligned/balance point, however, the achieved optimal fixation was very transient. After initial period of optimal fixation, higher amplitudes of drifts were seen.

Under aligned/balance point condition, all strabismic amblyopes could hold optimal fixation for transient period. This initial period of optimal fixation varied ranging from 30 seconds to 80 seconds (Table: 5-1). Hence initial 30 seconds (where there were no such high amplitude drifts for every strabismics) was compared with last 3 minutes (where higher amplitudes of drifts were always seen). The fixation of the AME was better for initial 30 second (Fig: 5-5) **(p=0.008)**.

Subject	**Period of initial optimal fixation (sec)**
XU	60
MA	38.4
OT	68.3
ST	80
MT	30
AD	42.2

Table 5-1: Period of initial optimal fixation

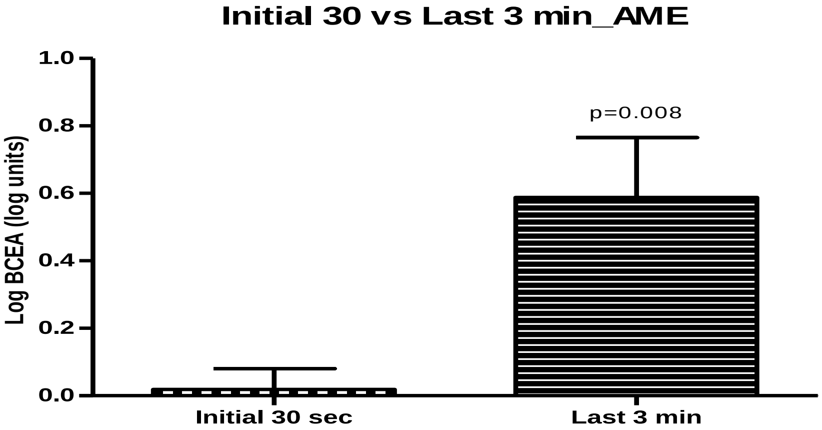


Figure 5-5: Initial 30 seconds vs. last 3 minutes

The fixation of AME was better for initial 30 seconds where the binocular summation was intact. After that initial period, higher amplitudes of drifts were seen.

5.2 Quantitative analysis of fixation stability:

The stability of fixation was quantified using two methods; 1) standard deviation of horizontal eye positions and 2) BCEA.

5.2.1 Standard deviation of Horizontal eye positions (fixation error):

5.2.1.1 Normal observers:

Fixation error in the covered eye (0.6±0.43) was higher than viewing eye in monocular viewing condition (0.33±0.12) and binocular viewing (0.36±0.1). However, no statistical significance was found across the conditions [p=0.129].

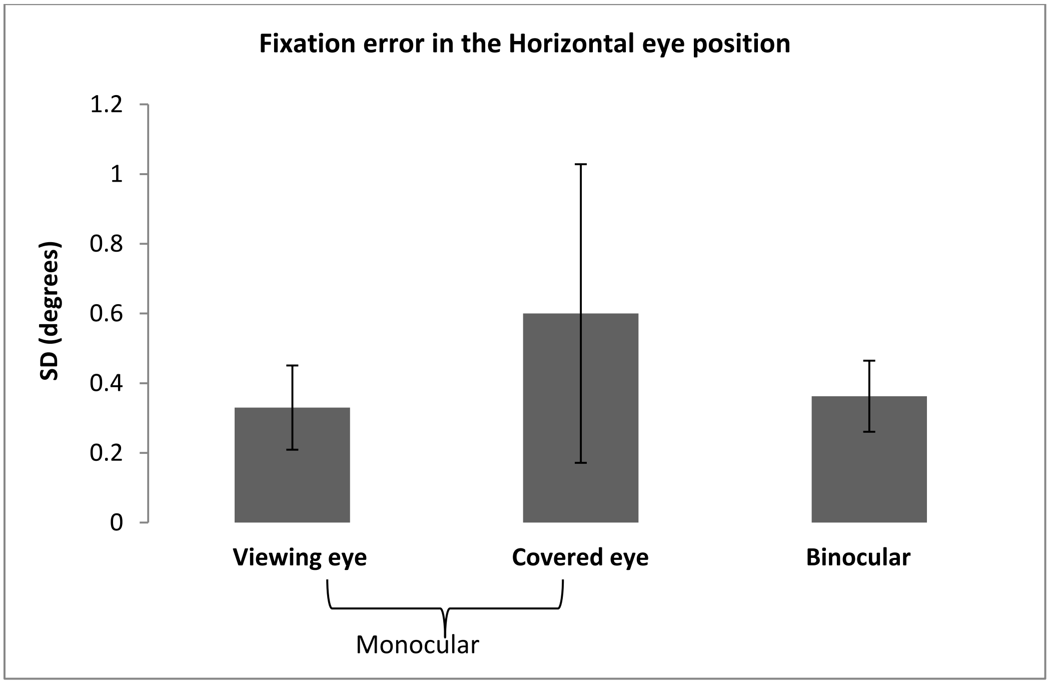


Figure 5-6: Fixation error in the horizontal eye position of Normal observers.

5.2.1.2 Strabismic amblyopes:

In strabismic amblyopes, on comparing FFE and AME using repeated measures ANOVA revealed a significant main effect between AME and FFE [F (1, 5) = 17.297; p=0.009]. Tukey HSD was performed and it showed that the fixational error of AME significantly reduced when the strabismus was aligned and the contrast was reduced to FFE (p=0.033). Moreover, under unaligned condition, the fixation error in the AME was significantly higher than that of FFE (p=0.018). However, the difference between FFE and AME was reduced when the strabismus was aligned (0.99) (aligned/high contrast) and the contrast was reduced to FFE (0.987) (aligned/balance point) [Fig: 5-7].

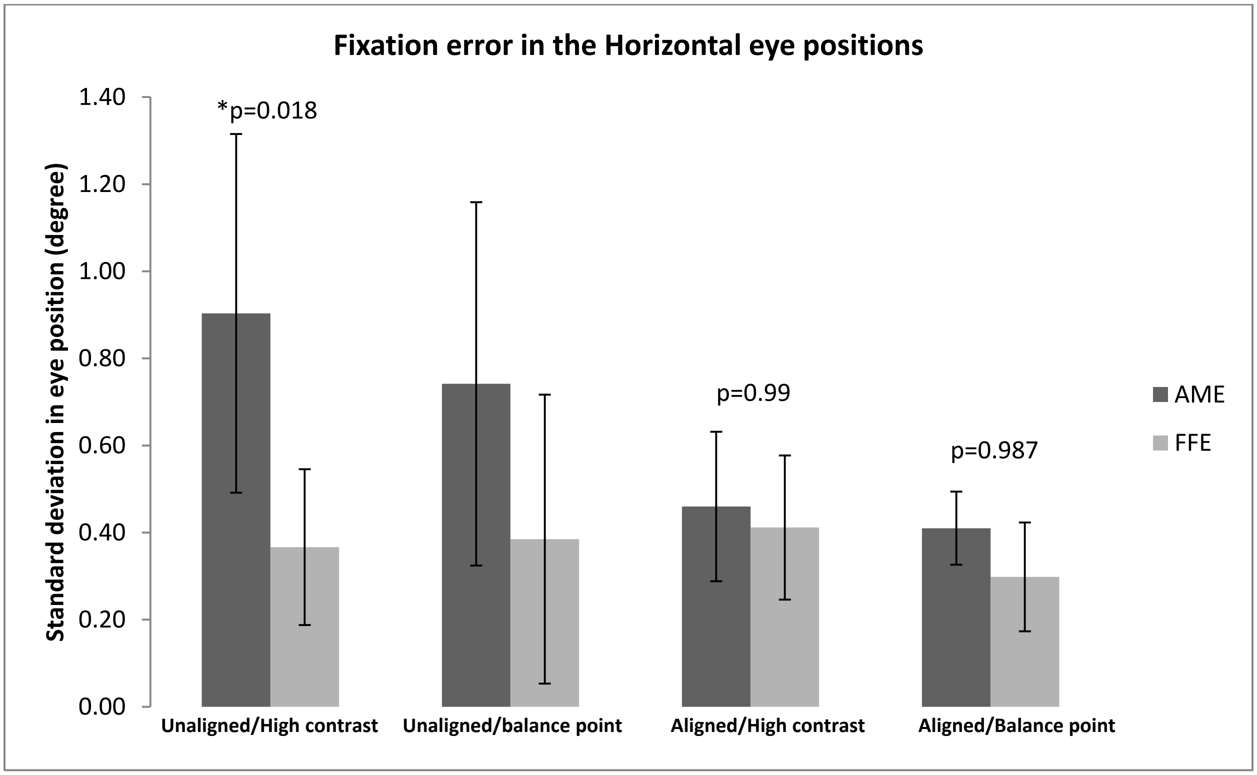


Figure 5-7: Fixational error in the horizontal eye positions of strabismic amblyopes

5.2.2 Bivariate Contour Ellipse Area (BCEA):

The values of BCEA were transformed into log values to perform parametrical analysis.

5.2.2.1 Normal observers:

The fixation eye movements were measured for both eyes while one eye fixated the target and the other eye viewed a uniform black sheet of paper. The results have suggested that the BCEA of the viewing eye (-0.26±0.25) was statistically significant than the BCEA of non-viewing eye (0.07±0.33) [p=0.0149]. It implies that viewing eye had better fixational stability than the non-viewing eye. However, when both eyes were looking at the target, the fixation stability of both eyes was calculated by averaging the values of right eye and left eye. The stability of fixation under binocular viewing (-0.24±0.16) was as same as the viewing eye under monocular condition. The results are shown in the Fig: 5-8.

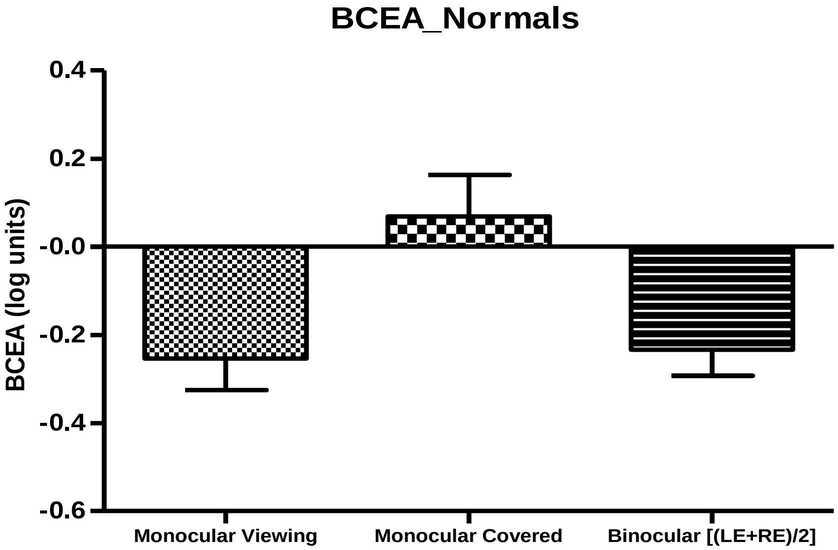


Figure 5-8: BCEA of normal observers

5.2.2.2 Strabismic amblyopes:

In strabismic amblyopes, the results were analyzed in two different ways, 1) separately for AME and FFE and 2) Binocular BCEA (by averaging the values of FFE and AME). In strabismic amblyopes, on comparing FFE and AME using repeated measures ANOVA revealed a significant main effect between AME and FFE [F (1, 5) = 18.697; p=0.008]. Tukey HSD was performed and it revealed the following results.

AME of strabismic amblyopes:

Fixation stability of AME significantly improved when the strabismus was aligned (aligned/high contrast = 0.19±0.28) [p=0.015] and it improved further when the contrast was reduced to FFE (aligned/balance point = 0.018±0.15) [p=0.0009] than unaligned position (unaligned/high contrast = 0.62±0.3). Though the fixation stability was better after reducing the contrast to the FFE (aligned/balance point) comparing to aligned/high contrast, there was no statistical significance (p=0.738) between the two conditions. The results are shown in the Fig: 5-9. Fixation stability of FFE was always the same under different conditions (Fig: 5-10).

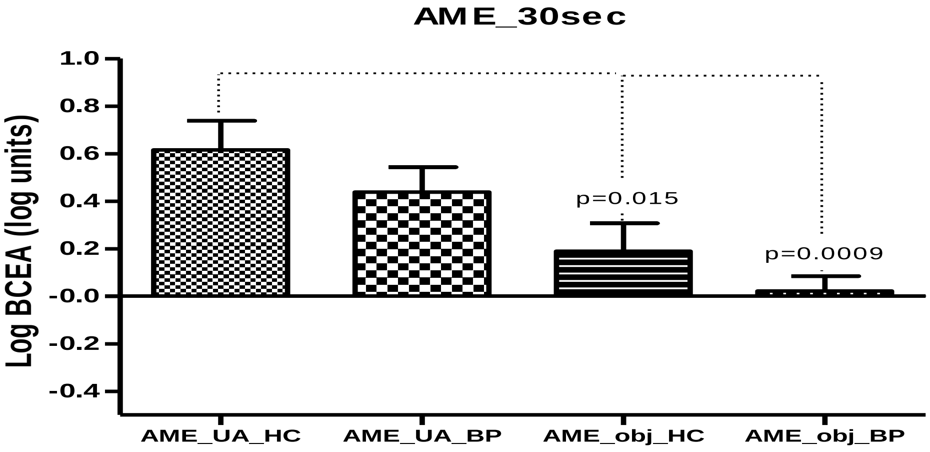


Figure 5-9: BCEA of AME

Log BCEA of AME plotted as a function of conditions. The above figure is showing that the BCEA of AME was better when the objective angle of strabismus was aligned (foveal fixation) than in unaligned position (p=0.015). The BCEA of AME was even better when strabismus aligned (foveal fixation) and when the contrast was reduced to FFE (p=0.0009) compared to unaligned position. Abbreviations used: AME – Amblyopic eye; HC – High contrast; BP – Balance point; Obj – Objective angle aligned; UA – Unaligned.

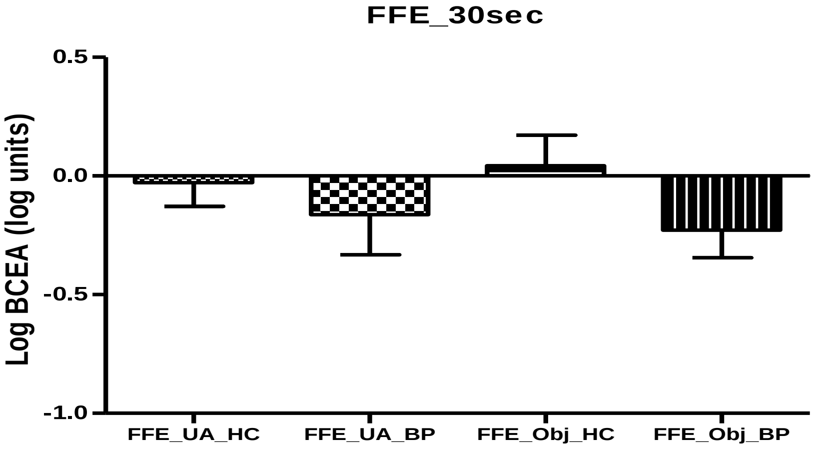


Figure 5-10: BCEA of FFE

The quality of fixation of FFE (BCEA) was the same across the conditions. Abbreviations used: FFE – Fellow fixing eye; HC – High contrast; BP – Balance point; Obj – Objective angle aligned; UA – Unaligned.

Binocular BCEA:

These measures were all under binocular viewing condition and therefore Binocular BCEA was calculated by averaging the $BCEA_{FFE}$ and $BCEA_{AME.}$ Binocular BCEA values have also suggested that binocular fixation was more stable when the strabismus was aligned and the contrast was reduced to FFE (-0.1±0.19) [p=0.0275] than unaligned position (0.42±0.27).

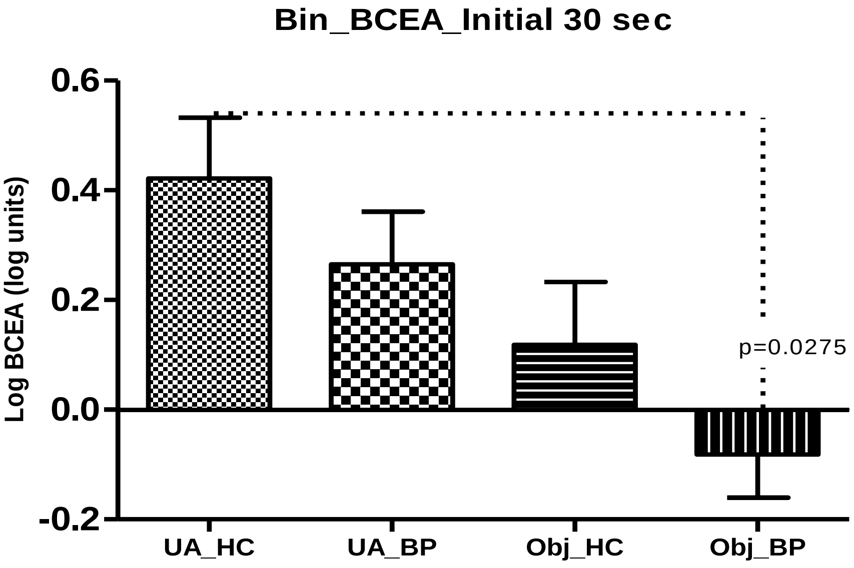


Figure 5-11: Binocular BCEA of strabismic amblyopes

Binocular BCEA was calculated by averaging the BCEA of FFE and AME. The same pattern was noted in Binocular BCEA as well. The binocular fixation was better when the objective angle was corrected. The binocular fixation was even better when the strabismus was aligned and also when the contrast was balanced between FFE and AME. Fixation stability was significantly better when the strabismus was aligned and the contrast was balanced between FFE and AME (Obj_BP).

5.2.2.3 Strabismic amblyopes vs. Normal observers:

All conditions for the binocular BCEA of aligned/high contrast and aligned/balance point were compared with binocular BCEA of normal participants. Statistical significance was found between aligned/high contrast and normal binocular BCEA (p=0.0205). But no statistical significance was found between aligned/balance point and normal binocular BCEA (p=0.1232).

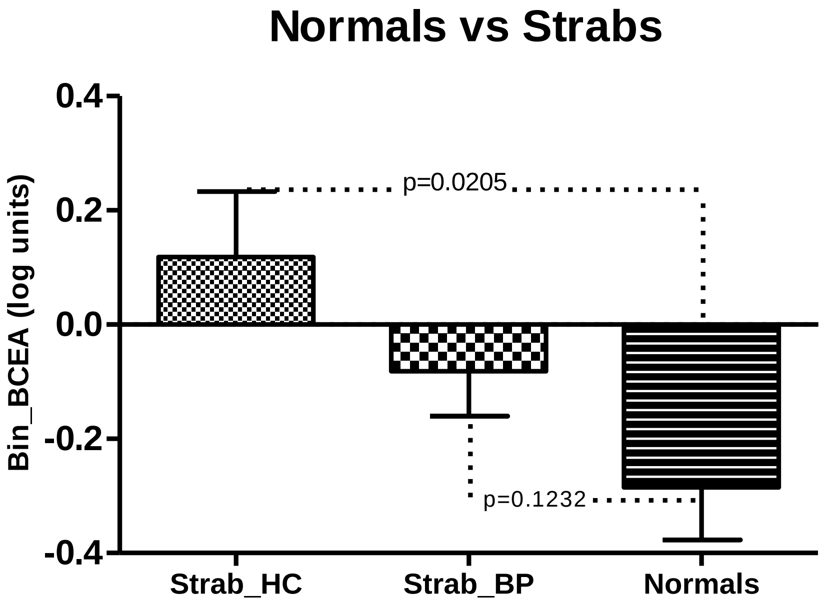


Figure 5-12: Strabismic amblyopes vs. Normal observers

The above results have suggested that the fixation was better and closer to normals only when the contrast was reduced to FFE (aligned/balance point.

5.3 Direction of drifts:

The drifts seen in the strabismic amblyope after aligning the objective angle of strabismus have the same direction as the direction of strabismus, i.e. strabismics revert back in the direction of original deviation (Figures 5-11 and 5-12).

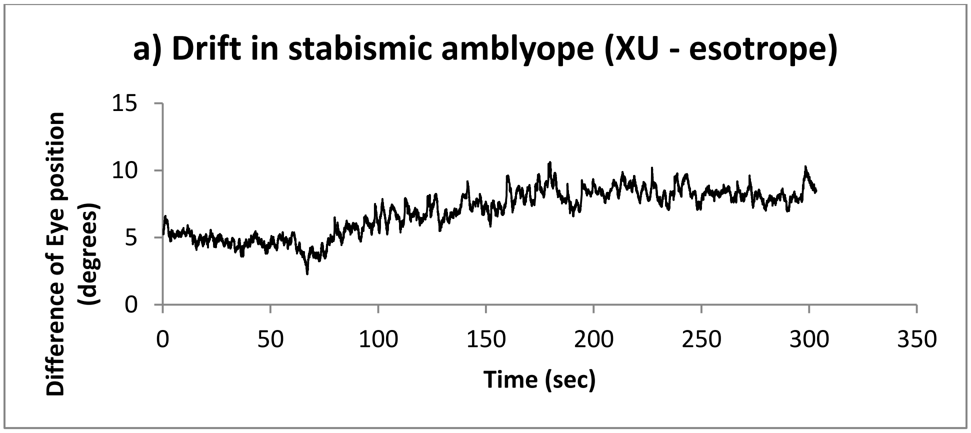


Figure 5-13: Direction of drifts in the strabismic participant (XU), an esotrope

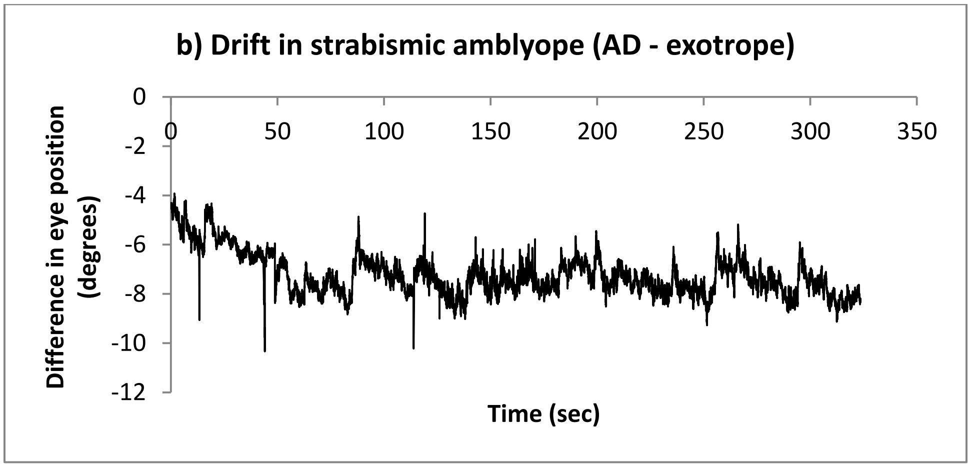


Figure 5-14: Direction of drifts in the strabismic participant (AD), an exotrope

The eye traces (figures-5-11 and 5-12) were plotted by difference of the horizontal eye positions of AME and FFE as a function of time (under the condition of aligned/balanced point); a) XU is an esotrope and showing increase in eso deviation after initial optimal bi-foveal fixation, b) AD is an exotrope and showing increase in exo deviation after initial optimal bi-foveal fixation.

5.4 Correlation of horizontal eye position:

The value of correlation coefficient gives the information of nature of eye movements and its conjugacy. In other words, high positive correlation suggests that the eye movement is conjugative [saccadic eye movement] whereas the high negative correlation suggests that the eye movement is disjunctive. Hence, Pearson’s correlation coefficient between horizontal eye positions was calculated for every fixational eye movements. The results are tabulated in the tables: 4-6 (strabismics) and 4-7 (normals).

	STRABISMIC AMBLYOPES						
	Whole 5 minutes				Initial 30 sec		
Participant	UA_HC	Obj_HC	Obj_BP		UA_HC	Obj_HC	Obj_BP
MA	-0.28	0.17	0		0.22	0.22	0.4
XU	-0.05	-0.87	-0.64		-0.71	-0.8	0.27
OT	-0.51	-0.45	-0.4		0.25	-0.6	0.08
ST	0.09	0.37	-0.05		0.26	0.2	0.12
MT	-0.14	-0.33	0		0.63	0.65	0.62
AD	-0.1	-0.09	0.24		0.32	0.05	0.55

Table 5-2: Correlation coefficients of horizontal eye positions in strabismic amblyopes during fixation

	NORMALS		
Participants	RE viewing	LE viewing	Binocular viewing
ARH	-0.02	0.04	0.2
VJ	-0.38	0.06	-0.57
YHH	-0.22	0.19	-0.18
SM	0.16	0.57	0.56
RJ	-0.52	-0.26	-0.49
CH	0.43	0.54	0.27

Table 5-3: Correlation coefficients of horizontal eye positions in normals during fixation

Chapter 6: DISCUSSION

This is the first study to look at the effect of ocular alignment and inter-ocular suppression attenuation on binocular fixation patterns. As discussed above, Gonzalez et al (2012)[13] used the BCEA analysis to confirm fixation instability under both monocular and binocular viewing in normal and amblyopic eyes. Control subjects showed significantly better fixation viewing binocularly compared with monocular viewing. This suggested that binocular input improved fixation. Fixation of the amblyopic eyes confirmed its high variability compared to the fellow eye and controls. Unlike the controls, fixation variance was not significantly improved with binocular fixation. Since the binocular improvement of fixation was improved only in controls and not the amblyopes, they concluded that the lack of binocular summation in the amblyopes was responsible for the overall decreased fixational stability and the lack of binocular improvement. However, in strabismic amblyopes, reduced binocular integration could be due to two, not necessarily independent factors; lack of bi-foveal stimulation and inter-ocular suppression. Thus a hypothesis was developed that in strabismic amblyopes, fixational error would be reduced following ocular alignment and eliminating inter-ocular suppression by contrast balance between two eyes. The results of this research support this hypothesis where fixational patterns became less variable when eye alignment was achieved and further improved when the eyes where aligned and contrast levels balanced. In this study, the fixation stability was measured using two methods; 1) simply the standard calculation of standard deviation of horizontal eye positions and 2) broader analysis using global BCEA. The main difference is that the latter involves standard deviation of both horizontal and vertical eye positions and also the correlation between horizontal and vertical eye positions. The BCEA provides an area of ellipse in which the fixation was lying for 68.2% of the time. The major axis of the ellipse would give the information on horizontal eye position whereas the minor axis provides the information on vertical eye position. Thus the BCEA is not limited to only one direction.

The standard deviation of the fixational eye positions in this study were not matched with the values shown in the previous studies which can be attributed to spatial (0.15°) and temporal (60Hz) resolutions of our eye tracking system. The eye tracking systems used in the previous studies [e.g. EyeLink II by Gonzalez et al, 2012 = 0.6'] had better spatial and temporal resolution systems. However, the effect of this lower spatial resolution was constant as this study concentrated on the relative change in the fixational stability with different viewing conditions. Moreover, though the spatial and temporal resolutions of our eye tracker are 9' and 60Hz, the results suggested that it is sufficient enough to delineate the differences between normals and strabismics.

6.1 Fixation stability in normal observers

In normal observers, monocular fixational stability was measured while one eye viewed the target and the other was viewing a black chart (i.e. no target to fixate). This was done in an attempt to mimic the suppression in amblyopes. A special effort (room lights were dimmed) was taken for few subjects who have experienced rivalry on viewing the black screen. The results suggested that eye which was viewing the target had better fixational stability than the non-viewing eye. This suggested that visual information acts to reduce fixational variation. This result was consistent with the results of Gonzalez et al (2012). Hence it was expected that in amblyopes under binocular condition, suppression of visual information from the AME might be responsible for poorer fixational stability. However, under their binocular viewing condition, the fixation stability was not significantly improved over the monocular viewing condition. Moreover, the binocular summation ratio was 1.9 for normals while binocularly viewing. It should be noted that the binocular summation ratio of 1.9 is higher than usual ratio of 1.4 (√2). Therefore, the summation for motor processes seems to be an additive process.

In this study, the targets were presented in dichoptic setting whereas it is not the case in the study by Gonzalez et al (2012)[13]. Therefore, there were few drifts seen in normal observers as well. Though this result was consistent with the results of Krauskopf et al (1960)[27], Gonzalez et al (2012)[13] have argued that the fixation should be more stable under binocular condition than monocular condition due to binocular summation.

6.2 Fixation stability in strabismic amblyopes

In the previous literatures, it has been depicted very well that the AME has poorer fixational stability than the FFE. This finding has been attributed to spatio-temporal visual deficits in the AME [13], poor visual acuity in the AME[52] and recently, reduced stereo acuity[52]. Subramaniam et al (2013)[52] showed a positive correlation between visual acuity and BCEA in the AME. However, by looking at the subgroups of amblyopes, anisometropic amblyopes had poorer correlation between visual acuity and BCEA whereas the strabismic amblyopes had high positive correlation between visual acuity and BCEA. Gonzalez et al (2012) [13] also found no correlation between visual acuity and fixational stability. Collectively, these results suggested that the visual acuity is not a major factor for poorer fixational stability in the amblyopes. Since, there is a positive correlation between stereo acuity and poor fixational stability, implied that the loss of binocular integration in amblyopes could be attributed to poorer fixational stability.

As stated earlier, the main objective of the study is to check whether the ocular alignment and balanced monocular inputs (attenuation of inter-ocular suppression) would improve the fixational stability in strabismic amblyopes. The fixation stability under binocular viewing was tested in four different conditions; 1) unaligned/high contrast, 2) unaligned/balance point, 3) aligned/high contrast and 4) aligned/balance point. Both SD and BCEA methods have suggested that the fixation of AME was more stable in aligned positions (aligned/high contrast and aligned/balance point) than unaligned positions.

6.3 Effect of aligning strabismus:

The results showed that, the fixation stability of AME improved (lower mean BCEA) when the objective angle of strabismus was corrected (Figures: 5-7 and 5-9) i.e. when THE fovea was stimulated. There was a study done by Bucci et al (2009) where saccades and vergence eye movements were quantified pre and post squint correcting surgery. They showed that the gains of vergence and saccades improved after surgery. Recently, Hertle et al (2009 a, b) [16,17] have shown that the fixational stability improved after extra ocular muscle surgery on infantile esotropia. However, it should be noted that these squint correcting surgeries have direct effect on ocular muscles (Hertle et al, 2009) and has little effect on the sensory processes. However, it should be noted that the alignment achieved through haploscope was transient (Table: 5-1).

6.4 Effect of attenuating inter-ocular suppression on fixation stability:

In amblyopes, there is loss of binocularity in the central field which was evident from the lack of binocular summation and loss of binocular functions like stereopsis [5,6,20,48]. Baker et al (2007) have showed normal contrast summation in strabismic amblyopes when the contrast to the dominant eye is attenuated. They also claimed that apparent lack of binocular function is due to substantial imbalance between monocular signals prior to the summation. There are animal studies which claim that binocular cortical cell functions could be restored by applying neuro-transmitters in the cortical area [28,39]. These results converge to a conclusion that summation, in strabismic amblyopes, is normal but suppressed [18]. Hence it implied that once the inter-ocular suppression is eliminated, many binocular functions would manifest. The result of this study has also shown that balancing the monocular inputs has an effect on fixation stability. The fixation stability of AME has further improved when the strabismus was aligned (foveal stimulation) and with reduced contrast to the FFE. It was also evident from the eye traces **[Figures: 5-3 and 5-4]** that the period of optimal bi-foveal fixation was prolonged in aligned/balanced point (bi-foveal and balanced monocular inputs) than in aligned/high contrast (mere bi-foveal stimulation).

6.5 Binocular fixational stability:

However, the measures of this research were under binocular conditions and therefore it is appropriate to look at combined (AME and FFE) fixation stability, i.e. binocular fixation stability in strabismic amblyopes. The measure of binocular fixation stability (binocular BCEA) showed that the fixation stability was significantly improved when the strabismus was aligned and provided with balanced monocular inputs (Figure: 5-11). Interestingly, when the binocular BCEAs (aligned/high contrast and aligned/balance point) of strabismic amblyopes were compared with binocular BCEA of normal observers, the binocular fixational stability of strabismic amblyopes was comparable to binocular fixational stability of normal observers.

The results have suggested that fixational stability appears to improve with ocular alignement and attenuation of inter-ocular suppression. However the improved stability in itself is only transient and is unable to overcome the established pattern of the strabismic angle which returns in less than one minute resulting in reduced fixation stability.

6.6 Restoring original deviation of strabismus

However the pattern of optimal fixation is for a brief period of time (figures: 5-3d & 5-4d). The AME show a drift which was in the same direction of as the original angle of the strabismus after that period of optimal fixation. This was noted in previous literature as prism adaptation, i.e. after correcting the objective angle of strabismus using appropriate prism, the eyes would drift back towards the original deviation [1,2,8,35]. In these previous studies, the prism adaptation in strabismics was compared to the fusional vergence in normal observers. Bagolini (1976b) [2] noted that in strabismics, the prism adaptation was slower and less precise compared to normal fusional vergence and termed this as anomalous fusional movements (afm). In normal observers, the fusional movements would bring the image on zero motorial point i.e. two foveas. However, in strabismics (early onset), the pattern of retinal correspondence is totally disturbed due to suppression in the central field (Sireteanu et al, 1989) [49]. Hence the zero motorial point in the deviated eye of strabismics is not fovea and so the image would be brought to a point (non-foveal) which has acquired zero motorial point

(Bagolini, 1976b) [2]. In strabismics, this zero motorial point usually is in the direction of deviation, i.e. esotropes would have it on nasal side of the retina whereas the exotropes would have it on temporal side of the retina.

6.7 Conjugacy of fixational eye movements:

As stated earlier, a high positive correlation between horizontal positions of two eyes suggested that the fixational eye movements are conjugate (Krauskopf, 1960)[27]. A high correlation doesn't always mean that the two eyes are working together; apparently one eye consensually following the other eye will end up showing high correlation between two eyes. However, the information of conjugacy of fixational eye movements was not clear from the results of this study (Table5-2). There was high variation in the correlation coefficient values in both normal and strabismic amblyopia groups. In strabismic amblyopes, if the conjugacy has improved with ocular alignment and attenuating inter-ocular suppression, then the values of correlation coefficients should have improved as well.

There are three types of fixational eye movements; 1) ocular drifts, 2) tremors and 3) microsaccades. Out of these, tremors and drifts are highly uncorrelated between two eyes and hence, for these eye movements, two eyes are independent. However, the fixational errors produced by these eye movements which are corrected by microsaccades are highly correlated between two eyes. Moreover, direction, duration and magnitude of the microsaccades are highly correlated between two eyes. If this is the case, under binocular condition, as quoted by Krauskopf et al (1960)[27] "*the two eyes operate independently to maintain their own fixation under binocular conditions has been shown to be false, for the saccades in the two eyes are correlated*". However, it should be noted that under binocular conditions, ocular drifts and tremors are independent between two eyes. Therefore, the number of microsaccades required to correct these errors will be higher. In other words, the frequency of microsaccades under binocular conditions might increase (Krauskopf et al, 1960). All of the above points on conjugacy hold true if the person tested is a normal observer. However, in the case of amblyopes where one eye has sensory dominance over the other eye, dynamics of the microsaccades might be completely different.

Gonzalez et al (2012)[13] measured rates of microsaccades in amblyopes under their three different viewing conditions (binocular viewing, monocular with normal eye fixating and monocular with amblyopic eye fixating) .No difference was found across these viewing conditions. However, they found a significant reduction of the frequency of microsaccades in binocular conditions compared with the monocular condition for normal observers. Since microsaccades are thought to realign the eyes when fixation is off target [27], then this is expected given the more accurate fixation seen in binocular viewing Therefore, the hypothesis proposed by Krauskopf et al (1960)[27] in relation to frequency of microsaccades under binocular viewing conditions, appears to be contradictory. Another detailed study of microsaccades on normal and amblyopic participants would help to answer these uncertainties on microsaccades.

Future Works:

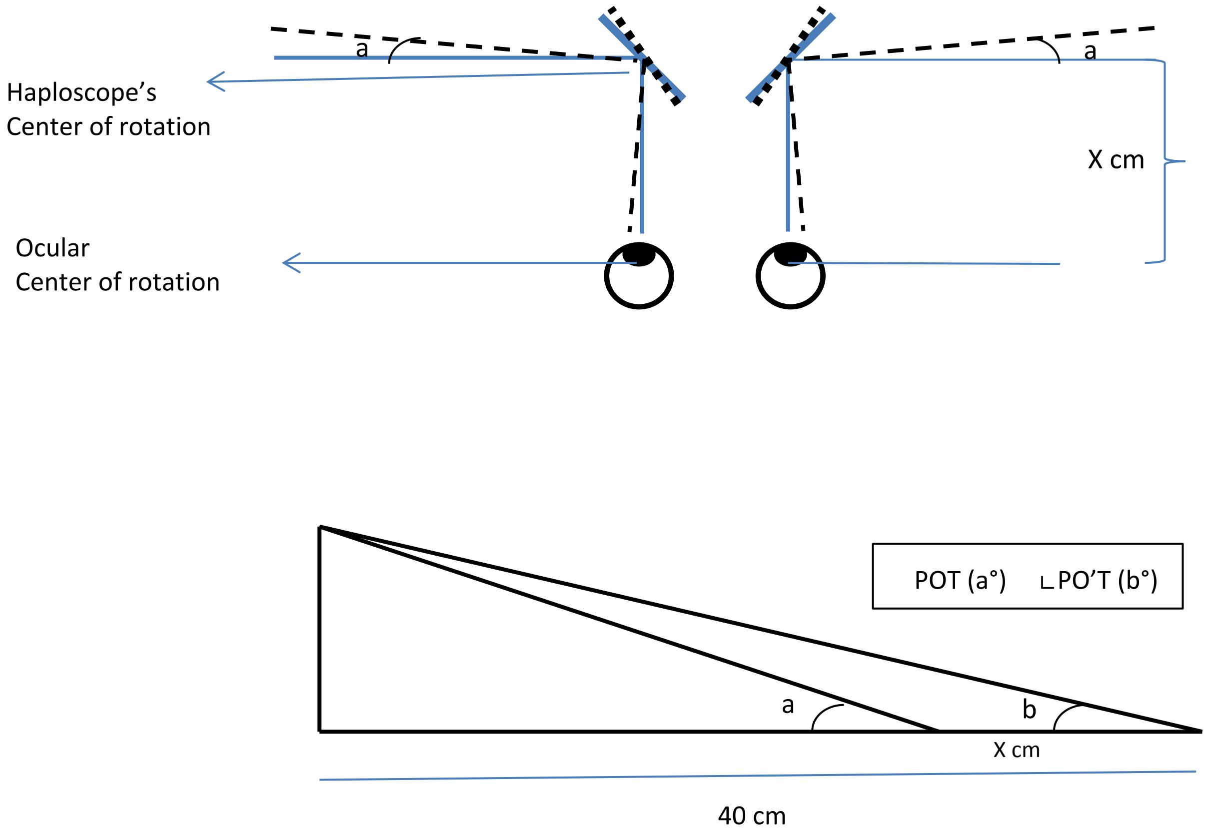
Therefore further explorations should be made to study the characteristics of microsaccades and ocular drifts, with ocular alignment and balanced monocular inputs, are needed to comment on conjugacy of fixational eye movements in strabismic amblyopes. It will also be interesting to explore the data further on estimating amplitude, peak velocity and main sequence of microsaccades with ocular alignment and balanced monocular inputs.

Upon haploscope alignment, all strabismic subjects showed a drift back to their original strabismic angle. The cause of this is not known. Since this limits the capacity for binocular summation, future efforts should be made to reduce or even eliminate this pattern. Such investigations could look at methods to make the fixation more active with greater attentional demands e.g. where dynamic moving stimuli are used. In addition changes could be made to the spatial frequency of the target in order to drive a more central (foveal) response. For instance, in this study, the task of the participant was to fixate at the target passively and this might be the reason for the amblyopic eye to drift back towards its original strabismus. Moreover, there were drifts in few normal observers. Therefore, in future, it will be interesting to look at the stability of eye movements during active fixation (i.e. some task while fixating). As noted earlier, microsaccades can be controlled during active fixation (i.e. task that requires visual attention) and thereby the stability of fixation might improve for a longer period (without drifting). Perhaps even subjects could be trained first. For instance, new anti-suppression therapies like Training using I-pod where the suppression is trained binocularly by playing tetris game is based on balanced contrast techniques. Our results suggested that fixation is drifted back towards original strabismus after a while maintaining an optimal fixational stability. Though it is uncertain that the strabismics would hold better fixation (without drifting) while playing tetris, it is assumed that the fusion lock (i.e. target seen by both eyes in the game interface) might help the strabismics to hold better. Therefore, the effect of fusional lock (central or peripheral) on fixational stability will also be studied in the future.

Conclusion:

In summary, stability of fixation can be transiently improved after aligning the strabismus and further improved after attenuating the inter-ocular suppression. This has suggested that the fixation stability in the amblyopic eye of strabismics appears to improve directly with the degree of binocular integration. However, further investigations are required to see whether binocular integration through contrast balancing will improve binocular eye movements such as vergence eye movements in strabismic amblyopes or that eye movements can be controlled to allow binocular integration.

Appendix A Haploscope – Optical theory



PT – Target displacement
O' – Haploscope's center of rotation
O – Ocular center of rotation
a – actual mirror rotation
b – actual ocular rotation

Figure 6-1: Optical theory of haploscope

As discussed (Chapter 4), the design of the haploscope was such that the Instrument's center of rotation was not coincident with the eye's centre of rotation. This is identified in 6-1.A. In Figure 6-1 A, the solid lines on the ray diagram represent the 'zero' position of the haploscope arms. The total optical length is 40 cm [i.e. distance between the center of ocular rotation and the target]. If x represents the separation between the haploscope arms' centres of rotation from that of the eye then the haploscope's center of rotation is at (40-x) cm from the target. If the arms are rotated to a given angle 'a' (Fig. 6-1), it is represented by dotted lines in Fig. 6-1 A. As the distance between the center of ocular rotation and the target is higher than that of the distance between the instrumentals' center of rotation and the target, the amount of angular rotation at the instrumental's center of rotation will be higher than at the center of ocular rotation.

In the second illustration (Fig: 6-1 B), the same information is showed with assumption of linear displacement instead angular displacement. PT represents the linear displacement of target which produces ∟PO'T (a°) at the distance of (40-x) cm [i.e. Instrumentals' center of rotation]. However, the center of ocular rotation is at 40 cm. Therefore, the same amount of linear displacement of target would produce ∟POT (b°) which is lower than that of ∟PO'T (a°).

Appendix B Gamma Correction

Gamma defines the relationship between pixel value and its actual luminance. In simple words, in any monitor, the relationship between the brightness of a portion of an object and the brightness of the corresponding portion of the image is generally non-linear. It is expressed by the formula

$$y = x^{\gamma}$$

where y is the magnitude of the output signal, x is the magnitude of input signal. So, 1/γ correction has to be done on the images to convert this non-linear relationship into linear relationship such that human eyes would perceive the exact luminance profile.

Aim:

The main aim is to measure gamma of the haploscope monitors.

Methods:

The haploscope monitor (7” diagonally, Lilliput®) was placed in line with a photometer (Konica-Minolta CS-100A). The photometer was focused to the center of the monitor. The monitor screen was kept complete black and then the luminance (i.e. brightness) of the monitor was increased in the steps of 10% (0 – 100%). Under a dark room condition, the luminance level was measured using photometer. Three measurements were taken for every luminance level.

Calculation of gamma:

The relationship between brightness (V), luminance (L) and gamma (γ) is defined as the following equation,

$$L = aV^{\gamma}$$

taking log on either side,

$$Log\ L\ - Log\ a\ = \gamma \mathrm{LogV}$$

Gamma was measured by plotting [log L – log a] as a function of log V. The constant ‘a’ is an offset, i.e. even at the zero brightness, the photometer would show luminance level and the luminance will be this offset value till the brightness reaches certain level.

Results:

The results were shown in the Table-1 and Figure-1. The gamma (slope) was calculated to be 2.1.

Brightness(v)	Log V	log a	Mean L	log L - log a
0	0.00	-0.38	0.42	0
0.1	-1.0	-0.38	0.42	0.0
0.2	-0.7	-0.38	0.42	0.0
0.3	-0.5	-0.38	0.42	0.0
0.4	-0.4	-0.38	0.42	0.0
0.5	-0.3	-0.38	0.65	0.2
0.6	-0.2	-0.38	4.25	1.0
0.7	-0.2	-0.38	20.22	1.7
0.8	-0.1	-0.38	47.20	2.1
0.9	0.0	-0.38	77.12	2.3
1.0	0.0	-0.38	105.17	2.4

Table 6-1: Values of Luminance

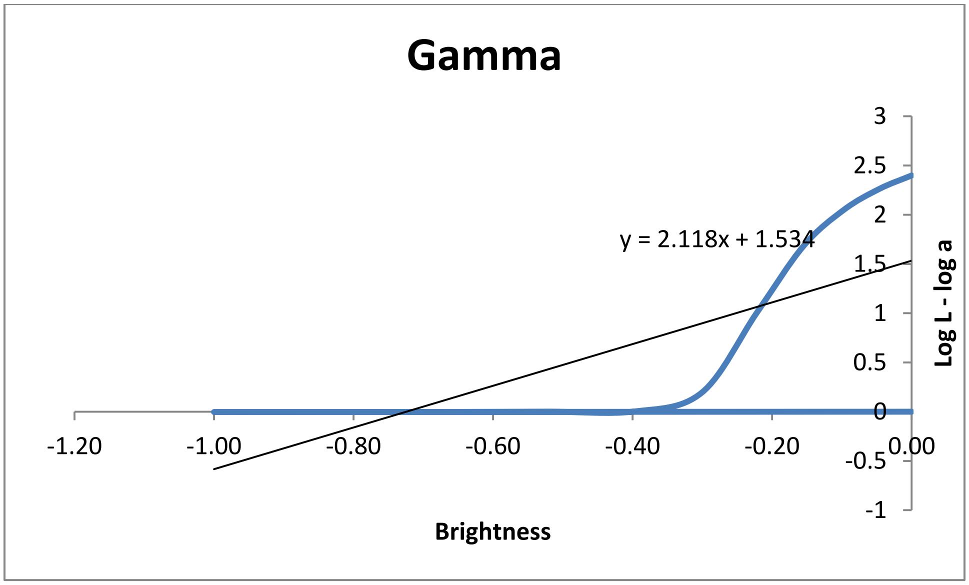


Figure 6-2: Gamma

Conclusion:

The results suggested that the monitor has gamma of 2.1 and the correction of 1/2.1 to be made in the image.

Appendix C Calculation of Weber's contrast

Calculation of Weber's contrast

Aim: To calculate various contrast level using Weber's contrast

There are two definitions have been commonly used for measuring the contrast of test targets: 1) Michelson contrast and 2) Weber's contrast. The Michelson contrast is usually measured for periodic pattern like sinusoidal grating and it is defined as,

$$C = \frac{L_{max} - L_{min}}{L_{max} + L_{min}}$$

where L_{max} and L_{min} are the maximum and minimum luminance levels of the target. The Weber's contrast is used to measure the local contrast of small test target on a large uniform background. It is defined as,

$$\boldsymbol{C = \frac{\Delta L}{L}}$$

where ΔL is the increment or decrement in the target luminance from the uniform background (L). Weber's contrast is usually within the range of -1 to ∞. The zero (0) being the black color, 0.5 being gray and one (1) being the white.

Methods:

The background of the target was gray (0.5). Hence the calculation was made to calculate different contrast levels of the target. The Table-1 shows the results of the calculation of the Weber's contrast.

Conclusion:

The calculated values were used in achieving balanced monocular input, e.g. in order to set the contrast of the image to 20% (i.e. reducing 90%), the value of 'I' should be 0.1 and 'I_b'

should be as always 0.5. Substituting these values in the above equation would set the contrast of the image at 20%

Feature Luminance	Background luminance	Weber's ratio	Contrast %
0	0.5	-1	-100
0.05	0.5	-0.9	-90
0.1	0.5	-0.8	-80
0.15	0.5	-0.7	-70
0.2	0.5	-0.6	-60
0.25	0.5	-0.5	-50
0.3	0.5	-0.4	-40
0.35	0.5	-0.3	-30
0.4	0.5	-0.2	-20
0.45	0.5	-0.1	-10
0.5	0.5	0	0
0.55	0.5	0.1	10
0.6	0.5	0.2	20
0.65	0.5	0.3	30
0.7	0.5	0.4	40
0.75	0.5	0.5	50
0.8	0.5	0.6	60
0.85	0.5	0.7	70
0.9	0.5	0.8	80
0.95	0.5	0.9	90
1	0.5	1	100

Table 6-2: Weber's contrast ratio

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