

**Effect of vergence adaptation and  
positive fusional vergence training  
on oculomotor parameters**

by

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## **Abstract**

Accommodation and vergence, the two important oculomotor systems, exhibit the property of adaptation which maintains the response for comfortable prolonged viewing. Several mathematical models have been developed to describe the basic underlying mechanism of accommodation and vergence. Currently used models contradict with each other in the placement of critical elements in the model. This thesis addressed this controversy and empirically verified these models. The effect of vergence adaptation and its influence on certain critical oculomotor parameters have been evaluated in two studies.

The specific aims, methods, results and conclusions of each chapter are as follows:

### **Chapter 3**

#### **Aim**

To evaluate the effect of vergence adaptation on convergence accommodation (CA) response and the effect of CA stimulation on accommodative adaptation to determine the model that best fits human accommodation and vergence interaction.

#### **Methods**

This study investigated the effect of vergence adaptation on the convergence accommodation (CA) response as a function of vergence stimulus magnitude and duration in 10 emmetropes. Convergence was induced using no prism, 6, and 12 prism dioptres as stimuli at 0.4m, viewed for 5, 10 & 15 minutes of duration in randomized separate sessions. Phoria measures and CA responses were recorded at the baseline, immediately following prism insertion and following specific durations of viewing through the prism (post-task). Also the effect of CA cross-link on

the tonic accommodation (TA) adaptation was investigated where TA response was measured before and after the convergence task.

### **Results & conclusions**

Repeated measures of ANOVA showed no significant ( $p > 0.05$ ) phoria adaptation or CA response change with no prism as the stimulus. For 6 and 12 prism dioptres, there were significant reductions ( $p < 0.01$ ) in CA with phoria adaptation. No significant ( $p > 0.05$ ) phoria adaptation or reduction in the CA response between 5, 10 and 15 minutes of viewing showing no effect of duration. No significant difference ( $p = 0.85$ ) between the pre and post task TA response while vergence was adapted. The results of the study show that vergence adaptation reduces CA response supporting models which predict the CA crosslink to reduce its output as tonic vergence adaptation progresses. However the convergence accommodation does not appear to lead to increased output of tonic accommodation.

## **Chapter 4**

### **Aim**

The purpose of this study was to evaluate certain critical parameters of vergence and accommodation under vergence adaptation (induced with a BO  $\Delta$ ), before and after positive fusional vergence training.

### **Methods**

Eleven emmetropes with normal binocular vision participated in the study. Distance & near phoria, AC/A & CA/C ratios, & positive fusional amplitude at near were evaluated before and after two weeks of positive fusional vergence training. Phoria adaptation and CA responses were

monitored every 3 minutes for 15 minutes while the subjects viewed through 12Δ BO under open-looped accommodation at 0.4m before and after training. On a separate vergence adaptation session (before training), phoria adaptation was induced under dual closed-loop condition using 12Δ BO at 0.4m. Cross-link ratios, BO fusional amplitude at 0.4m and near phoria were measured following 15 minutes of prism adaptation. Subjects underwent 2 weeks of positive fusional vergence training using variable tranaglyphs and aperture rule at 0.4m. Phoria adaptation and CA responses monitored over time were exponentially fit and were compared before and after training. AC/A & CA/ C ratios and BO to blur value at 0.4m taken before training, under the vergence adapted state and after training were analyzed using repeated measures ANOVA.

### **Results & conclusions**

No significant difference ( $p > 0.05$ ) in the cross-link ratios were found before and after training. However, there was a significant ( $p < 0.01$ ) increase and decrease in the AC/A and CA/C ratios respectively under the vergence adapted state. BO to blur value at 0.4m was significantly increased ( $p < 0.01$ ) from the pre training value under both vergence adapted condition and following training. Rate constants and magnitudes of phoria adaptation and CA response reduction were significantly ( $p < 0.01$ ) different following training demonstrating robust and greater magnitude of vergence adaptation in the BO direction reducing the CA response faster. However, this improved vergence adaptability is not reflected in the static measures of AC/A and CA/C ratios. The increased BO to blur value following training is caused by the increased speed of prism adaptation reducing the CA response during BO fusional amplitude testing.

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## **Dedication**

To my parents, brother and  
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# Chapter 1 REVIEW OF VERGENCE, VERGENCE ADAPTATION & TRAINING

## 1.1 Basic Concepts of Vergence

### 1.1.1 Definition and Mechanism

Evolution of frontal placement of the eyes has led to the achievement of binocular vision, a process by which the two visual fields overlap on each other to yield a single fused image of the visual scene. The purpose of binocular vision is to achieve fusion & perceive depth and judge distance by means of a visuosensory mechanism called stereopsis (Howard & Rogers., 1995). The human visual system maintains binocularity and stabilization of retinal images by means of six types of eye movement, such as saccadic, pursuit, vestibular, optokinetic, fixational & vergence and each type governed by discrete supranuclear control mechanism. Six extraocular muscles (4 recti, superior, inferior, lateral and medial and 2 obliques, superior and inferior) in each eye coordinate to move the eyes along x, y and z axes (Von Noorden, 1990). Horizontal movements take place along vertical axis, vertical movements along horizontal axis and torsional movements along an axis about the line of sight. The oculomotor nerve innervates superior, inferior, medial recti and inferior oblique, the trochlear nerve innervates superior oblique and the lateral rectus receives its innervation from the abducens nerve (Von Noorden, 1990).

Vergence, also referred to as disjunctive eye movement, rotates the two eyes simultaneously in the opposite direction (Westheimer & Mitchell., 1956; Westheimer & Mitchell., 1969) to place the fixated object on the corresponding retinal points by changing the distance of gaze. Vergence is usually expressed in terms of prism diopters ( $\Delta D$ ) or meter angles (MA). A MA is

the reciprocal of viewing distance in meters and is equivalent to the Diopter (D). The product of MA and inter-pupillary distance (IPD) in centimeters gives amount of vergence in  $\Delta D$ . Vergence eye movements can be horizontal, vertical or torsional. This thesis considered only horizontal vergence movements. Horizontal vergence is required to bifoveate objects when gaze is shifted between targets located at different viewing distances from the observer. A horizontal vergence towards the midline is referred to as the convergence and the one away from the midline is referred to as the divergence.

### **1.1.2 Vergence components**

Maddox (Maddox, 1886) classified components of vergence were clinically classified into four: Fusional, accommodative, proximal and tonic vergence. Disparity (Fusional) vergence is a psycho-optic reflex stimulated by the retinal disparity, which acts as the primary sensory stimulus to vergence (Stark et al., 1980). The angular positional difference at the eyes between an object in the field and the intersection of the lines of sight (bifixation point) is referred to as the binocular retinal disparity and specifies the spatial relationship of retinal images to corresponding points (Howard & Rogers., 1995). The locus of points stimulating corresponding retinal points giving rise to single vision is termed as horopter (Howard & Rogers., 1995). Retinal disparity is caused by an object that is lying off the horopter which does not fall on the corresponding retinal points. An object that is closer to the observer than the horopter would cause a crossed retinal disparity, which drives convergence, since the image would fall temporally from the corresponding points on the retinas and the observer would view the right eye's image to the left of the left eye's image. If an object is farther from the observer than the

horopter, an uncrossed retinal disparity, that drives divergence, would be caused since the image would fall nasally from the corresponding retinal points so that the observer would view the right eye's image as rightward of the left eye's image. A vergence response can also be evoked by blur driven accommodation resulting in accommodative vergence. The synkinetic interaction between accommodation and vergence is detailed in Section 1.1.3. Proximal vergence is evoked by the perceived nearness of an object (Borish, 2006). The contribution of proximal vergence to the overall vergence response is relatively high in the absence of disparity and blur cues and its impact is less under natural binocular viewing conditions where disparity and blur cues are present (Hung et al., 1996). In the absence of any innervation to the extraocular muscles, the eyes would adopt a divergent position of 15 to 25°, referred to as the anatomical position of rest (Stutterheim, 1934). In the absence of an adequate visual stimulus (like disparity, blur-driven accommodation and proximity), eyes would converge about 3°, referred to as the physiological position of rest (Owens & Leibowitz., 1980). Eyes are converged from the divergent anatomical position of rest to the physiological position of rest by means of tonic vergence innervation that reflects the baseline tonic neural innervation to the extraocular muscles (Cogan, 1948) and hence the vergence is termed as the tonic vergence (TV). Maddox (1886) described TV as a distance heterophoria measurement, however a significant difference has been demonstrated between them (O'Shea et al., 1988; Rosenfield & Ciuffreda., 1990) since tonic vergence is slightly more convergent than distance heterophoria.

### 1.1.3 Interaction between Vergence and Accommodation

Accommodation is a process by which the dioptric power of the crystalline lens of the eye is altered according to the vergence of the object to render a clear focused image on the retina (Fincham, 1951). The aggregate accommodative response has contributions from blur-driven (reflex) accommodation, vergence accommodation, proximal accommodation and tonic accommodation (Heath, 1956). Vergence and accommodation are tightly coupled by means of two neural cross-links to enhance the accuracy of the response through mutual contribution. Under natural viewing conditions, optically induced accommodation elicits a vergence response, termed accommodative vergence (AV) (Morgan, 1944; Alpern et al., 1959) and the disparity driven vergence initiates an accommodative response, termed as the vergence accommodation (VA) (Fincham & Walton., 1957; Kent, 1958; Morgan, 1968). The strength of the cross link from accommodation to vergence is evaluated by inducing changes in the accommodative stimulus and measuring the vergence response under monocular condition. The slope of the linear fit plotting accommodative stimulus (in D) and the vergence (in  $\Delta D$ ) response yields the stimulus accommodative vergence to accommodation ratio (sAV/A). The sAV/A ratio is reported to be  $4 \pm 2 \Delta D$  per Diopter (D) of accommodation (Alpern & Ellen., 1956) in normal individuals. In contrast, the slope of the plot using accommodative response and resulting vergence gives the response AV/A (rAV/A) ratio. The rAV/A ratio is found to be approximately 8% higher than the sAC/A ratio (Alpern & Ellen., 1956), the difference owing to the lag of accommodation. Similarly the magnitude of association from vergence to accommodation is determined by the vergence accommodation to vergence (VA/V) ratio and is measured by eliminating blur cue to accommodation and changing the stimulus to vergence and measuring the



resulting accommodative response. The slope of the linear fit plotting vergence stimulus (in MA) and accommodative response (in D) gives the stimulus VA/V ratio (sVA/V) and if the actual vergence response and accommodative response are plotted, it gives the response VA/V ratio (rVA/V). Since the vergence error (difference between stimulus and response) is small (Ogle, 1950), the difference between sVA/V ratio and rVA/V ratio is small. Studies have reported a range of values for the normal VA/V ratio. Normal value is reported to be 1D/MA of convergence (Fincham & Walton., 1957). These cross-link ratios are reported to be inversely related, meaning, an abnormal high AV/A ratio would produce a low VA/V ratio to maintain the stability of the response (Schor, 1992). Accommodation and vergence associated with pupillary constriction constitute the “near triad” when the fixation is changed from distance to near. AV and VA are the general terms to denote the cross-links. When accommodation drives convergence, it is termed as the accommodative convergence (AC) and when the convergence drives the accommodation, it is termed as the convergence accommodation (CA). For the purpose of this thesis, AC and CA are considered.

#### **1.1.4 Neural Control of Vergence**

There are several separate subsystems that have neural control over the eye movements whose effects are channeled through a final common path, the extraocular motoneurons (Keller & Robinson, 1972; Mays & Porter, 1984). Findings suggest that conjugate and vergence signals are generated separately and are combined at the extraocular motoneurons (Mays, 1984). The midbrain neurologic control of the vergence mechanism has been well studied over the past two decades; however has not been clearly defined. It has been suggested that the general neural

organization for vergence eye movements is similar to that of conjugate saccadic eye movements (Mays et al, 1986). Neurons that control the vergence mechanism (both convergence and divergence) have been found in the midbrain (Mays & Gamlin, 1995; Mays, 1984) in the mesencephalic reticular formation, 1 to 2 mm dorsal and dorsolateral to the oculomotor nucleus (Judge & Cumming, 1986; Mays, 1984; Mays et al, 1986). Similar to saccades, the final motoneuronal controller signal for convergence consists of a small and broad pulse combined with a step, where the pulse is responsible for the actual eye movement and the step for maintenance of final eye position. Three types of midbrain neural cells have been found (Mays et al., 1986): 1) vergence burst cells, 2) vergence tonic cells, and 3) vergence burst-tonic cells. When a disparity is presented, it undergoes sensorimotor transformation and a phasic vergence signal drives the vergence burst cells which fire before and during vergence. The output of burst cells is a vergence velocity signal producing the pulse response. Part of this vergence velocity signal serves as the input to the vergence integrator, whose output is a vergence position signal that drives the vergence tonic cells that fire in relation to vergence angle before the actual vergence movement to produce a step response. The vergence velocity signal combines with a vergence position signal to drive the motoneurons innervating the extraocular muscles responsible for that particular movement (Mays et al, 1986). Vergence burst-tonic cells carry both vergence velocity and vergence position signals that input directly to the oculomotor neurons and are referred to as “near response cells” (Mays et al, 1986). Though the midbrain consists of a majority of neurons that govern vergence, there also exist neurons that discharge during vergence in the pons (Rambold et al, 2004; Rambold et al, 2005), cerebellum (Westheimer & Blair, 1973) and in a few areas of the cerebral cortex such as the frontal eye field

(Gamlin & Yoon, 2000), parietal lobe (Hasebe et al, 1999), middle temporal and medial superior temporal visual areas (Takemura et al, 2001) and in the primary visual cortex (V1). Vergence and accommodation are tightly coupled and studies reported difficulty in distinguishing midbrain cells related to accommodation and vergence separately during near-response (Judge & Cumming., 1986).

For the purpose of this thesis, we will consider only convergence.

## **1.2 Accommodation and Vergence Interaction Models**

Application of control system theory to study the behavior of accommodation and vergence and their interaction has led to the development of different dual interaction models. These models attempt to quantitatively describe the behavior of the underlying physiological mechanisms that coordinate accommodation and vergence and their interaction. For clarity, an overview of basic control theory concepts and the physiological (accommodation & vergence) analogs to the control system components are outlined in this section.

### **1.2.1 Basic concepts of control system**

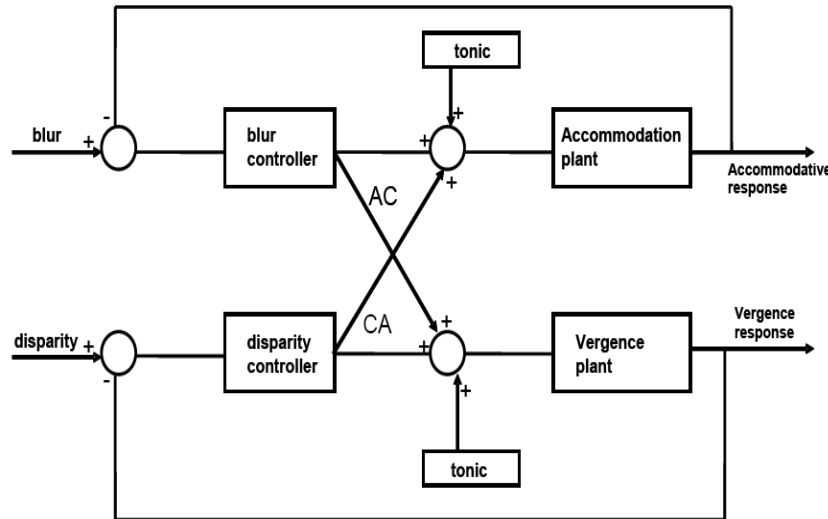
A control system is defined as an arrangement of physical components connected or related in such a way as to command, direct, or regulate itself or another system (DiStefano et al., 1988). Two terms that define or identify the control system are the input and output of the system. The input is the stimulus that is applied to the control system from an external source in order to produce a specified response from the control system. For example, blur is a stimulus to evoke an accommodative response and disparity is a stimulus to initiate a vergence response. The output is the actual response obtained from the control system and it may or may not be equal to the specified response implied by the input. Examples are change in the crystalline lens power to produce an accommodative response and movement of the eyes to produce a vergence response. The difference between the input and the output of the system is termed the error. In the accommodation system, lag or lead in the accommodative response is the error and in the vergence system, fixation disparity is considered as the error. These errors of accommodation and vergence are considered purposeful since they keep replenishing the systems' innervation

and thereby maintain the steady-state response without being decayed (Schor, 1979). Control systems are classified as open-loop and closed-loop, based on the control action that is responsible for activating the system to produce the response (DiStephano et al., 1988). In an open-loop system, the control action is independent of the response and in a closed-loop; the control action is contingent upon the response. In order to classify a control system, it is essential to distinguish the components of the system from the components that interact with, but are not part of the system. The characteristic feature of a closed-loop control system is a feedback mechanism that allows the response to be compared with the stimulus to the system so that an appropriate control action may be performed with an increased accuracy. Under natural viewing conditions (closed-loop), accommodation and vergence operate under negative feedback mechanisms that feed error information to the controller. The controller in the physiological sense refers to the neurological mechanism that generates neurological codes from the physical stimuli such as blur and disparity to drive accommodation and vergence. Two types of controllers have been identified (Schor, 1999). First, the proportional controller is a neurological mechanism that provides an innervation that is proportional to the magnitude of the stimulus (as a form of error signal). A physiological analog to this are phasic cells that drive the fast component of reflex accommodation and the fast fusional component of disparity vergence (Schor, 1999). These fast components respond rapidly to the blur and disparity stimuli and decay faster than the slow components when the stimulus is removed. Second, a leaky neural integrator stores up innervation in response to a stimulus and a small error is required to keep the stored response from decaying. A physiological analog to this are tonic cells that drive the slow component of reflex accommodation and disparity vergence and are responsible for maintaining

a stable response through adaptation (Schor, 1999). The decay of the slow component is relatively slow when compared to the fast component. The controller generates an appropriate signal to drive the plant. Plant is that physiological component that produces the desired action. The crystalline lens and the ciliary body zonules are represented as the plants of accommodation and the extraocular muscles are represented as the vergence systems' plant.

### 1.2.2 Model of accommodation and vergence

A schematic of the basic negative feedback model of accommodation and vergence interacting via the cross-links, the AC and the CA is shown in figure 1.1

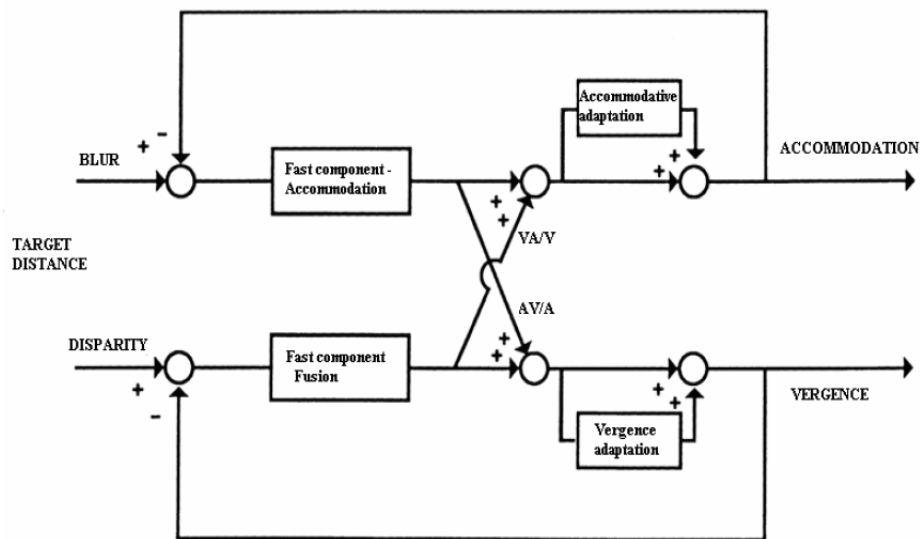


**Figure 1.1 Dual interaction model of accommodation and vergence with cross-link interactions AC and CA. Model adapted from Hung & Semmlow, 1980.**

Under normal binocular viewing conditions, both accommodation and vergence operate under closed-loop conditions and the responses are obtained in the presence of visual feedback. When the stimulus is presented, in the form of blur and disparity, the respective controllers initiate the response. They also drive their respective cross-link that feed into the opposite system. The output of the controller and the crosslink are summed at the summing junction where tonic input is added on to give the net response elicited by the plants (crystalline lens, ciliary body zonules& extraocular muscles). The accommodative and vergence errors are fed back into the respective controllers via the feedback loop to maintain a stable response.

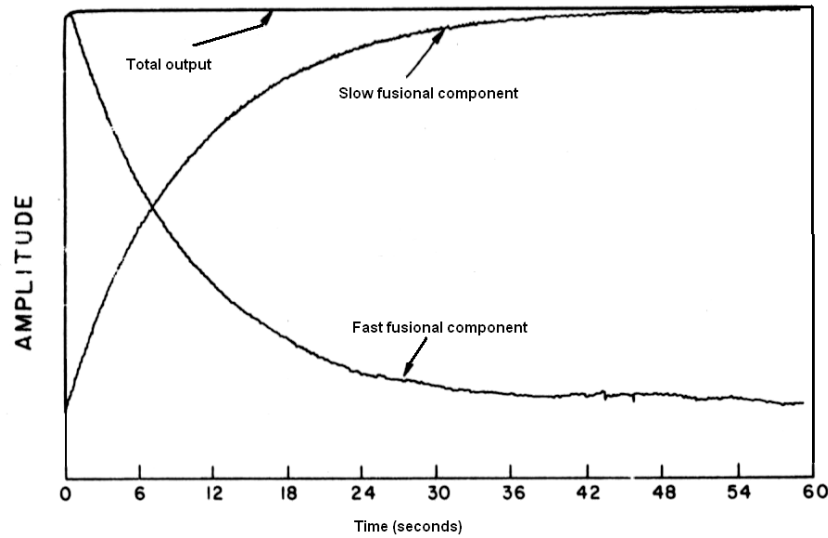
### 1.2.3 Basic adaptation model

Adaptation plays a critical role in maintaining a sustained closed-loop response. Basic concepts and underlying mechanism of adaptation have been detailed in the vergence adaptation section 1.3. For the purpose of this thesis, only vergence adaptation has been considered; however, an analogous mechanism exists for accommodation. The general adaptation model of accommodation and vergence consists of a controller comprising of a transient (fast) component and a sustained (slow) component (Schor, 1979). The fast controller gives input to the slow controller and to the cross-link. The fast controller executes the initial response which is independent of visual feedback (open-loop response). Upon prolonged viewing, with continuous stimulation of the fast component, the slow component takes over the response reducing the fast component output and this due to negative feedback. This is shown in figures 1.2 & 1.3.



**Figure 1.2 Adaptation model of accommodation and vergence showing fast and slow components with the slow component exhibiting the adaptation. The cross-link components are placed between fast and slow controllers. Model adapted from Schor 1992.**



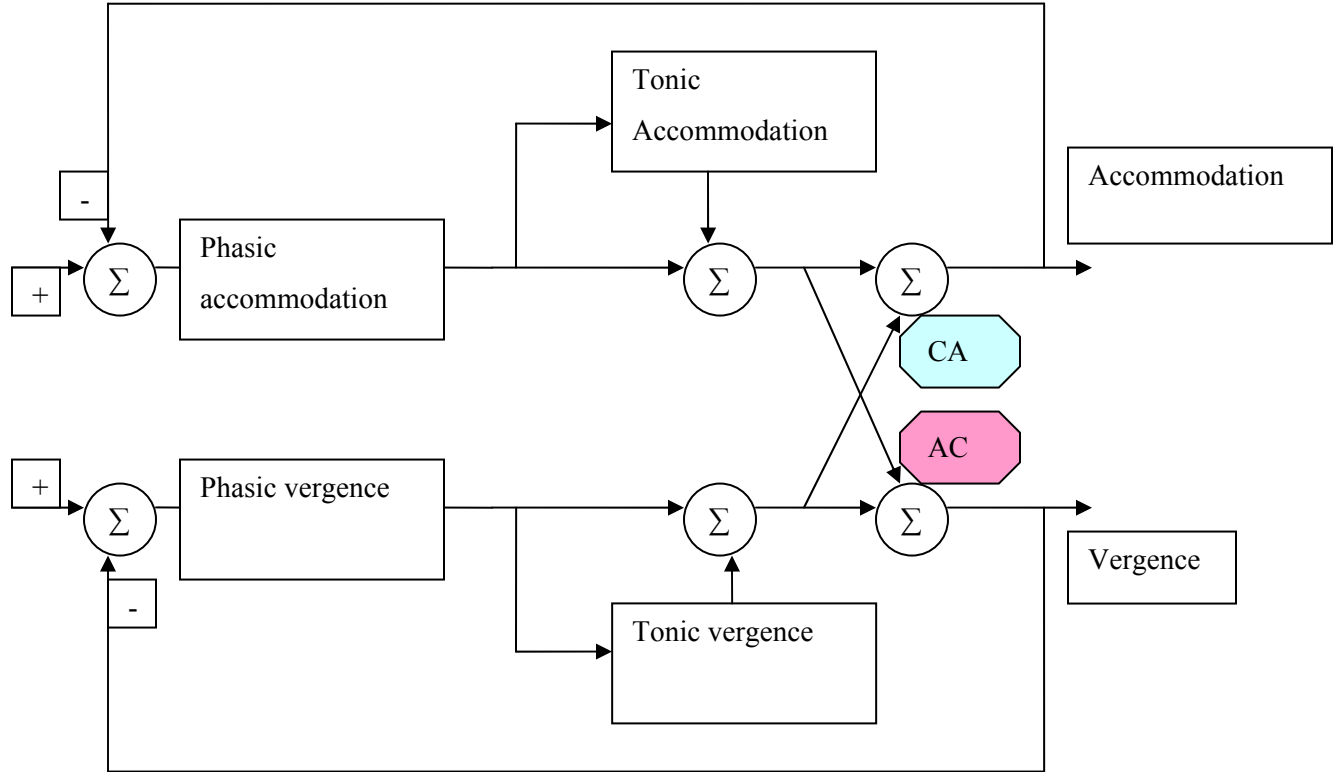


**Figure 1.3 showing concomitant reduction of fast fusional component output with the increase in the output of slow fusional component with sustained fixation. The output of the slow fusional component demonstrates vergence adaptation. Reprinted with permission from Schor (1979); Relationship between vergence eye movements and fixation disparity, Vision Research 19(12) 1979 © Elsevier.**

#### **1.2.4 Controversy in the current models**

Different computational mathematical models have been developed in order to demonstrate the basic mechanism of accommodation and vergence and their interaction. One controversy has been in the placement of the cross-link components in the forward loop. The model developed by Schor (1992) (from figure 1.2) has the cross-links originate between the fast and the slow components of blur and disparity controllers and that the cross-links receive input from the fast components. Accordingly, the model predicts that when the system adapts and the slow component takes over the response, the reduction in the fast component output eventually reduces the cross-link output as mentioned earlier. Hence, vergence adaptation would reduce the CA magnitude and accommodative adaptation would reduce the AC magnitude. In contrast,

Ebenholtz and Fisher (1982) proposed an alternative model (shown in figure 1.4) based on their experimental data, which suggests that the crosslinks originate after the slow controller. Accordingly, the cross-links receive input from both the fast and the slow components and not just from the fast component. Hence adaptation of the system would not affect the cross-link magnitude. The model was developed from empirical testing in which the change in the tonic vergence with vergence adaptation induced by a sustained blur-driven accommodation task through the AC/A cross-link was measured. An inverse relationship between the accommodative demand and the change of heterophoria before and after adaptation was found. The results suggested that tonic vergence is stimulated by the output of phasic vergence, but not by the accommodative vergence crosslink. When accommodative vergence increases with increasing accommodative demand, under closed-loop vergence, the phasic component of vergence would be reduced in order to maintain a vergence response equal to a constant demand. If the tonic component were stimulated by both phasic and crosslink components, the change of the tonic posture after adaptation would be independent of the magnitude of the crosslink component. However, if the tonic component was stimulated by the phasic component alone, the change of the tonic posture would be inversely related to the magnitude of the crosslink component.



**Figure 1.4 showing simplified Fisher and Ebenholtz model depicting the cross-links originating after the slow (tonic) controller. Model adapted from Fisher & Ebenholtz., 1982.**

Several studies have been conducted to empirically verify these models. Some of them support Schor's model while others support Ebenholtz and Fisher model. Experiments described in this thesis address this controversy and the results could help in determining the model that best fits to the human accommodation and vergence systems.

## **1.3 Vergence Adaptation**

### **1.3.1 Basic concepts and mechanism**

The ability of the biological systems to adapt to changing conditions in the external environment balances the systems' existing level of action with the demand level from the environment so that the systems attain the entire range of the transient response (Hung, 1992). When a prism is placed in front of the eye, the disparity between the images of the eyes is sensed by the vergence system to rotate the eyes in an appropriate direction to achieve fusion and this is accomplished by the act of the fast fusional vergence mechanism. If the vergence feedback loop is opened, by occluding one eye, the fast fusional vergence response decays to the tonic value. But when the binocular viewing is sustained for a longer time, say more than 1 or 2 minutes, the fast component response is replaced by the slow component response which is manifested as the change in the heterophoria to the baseline value and has been referred to as vergence adaptation (Schor 1979). The onset of the slow fusional vergence response reduces the output of fast fusional vergence response in order to maintain the aggregate vergence response (shown in figure 1.3). The purpose of vergence adaptation is to reduce the load on the fast fusional vergence mechanism (Schor, 1983). When the fusion is broken and feedback loop is opened, the fast fusional vergence response decays faster but the open-loop vergence response remains closer to the binocular closed-loop response for few minutes due to slowly decaying slow fusional vergence. This response is reflected in the post-task increase in the tonic vergence response as vergence adaptation, although tonic vergence innervation remains constant (Rosenfield & Gilmartin, 1988). The amount of vergence adaptation increases with increased magnitude of the adapting stimulus (Sethi & North., 1987). The mean time for the regression of the vergence

adaptation to the baseline value was evaluated by Fisher et al (1990). They observed a rate of decay of vergence adaptation inversely proportional to the duration of the adapting stimulus and an initial magnitude of adaptation linearly related to the stimulus duration.

Clinically, vergence adaptation has been demonstrated as prism adaptation where an ophthalmic prism is induced before the eyes. The heterophoria measured after a period of binocular viewing through the prism is equivalent to that of the baseline phoria that is obtained before the introduction of the prism. The way the oculomotor system adapts to the horizontal ( $6\Delta$ ) and vertical ( $2\Delta$ ) disparities was tested in normal individuals by Henson & North (1980) at both distance and near viewing distances. Their results showed that following 3-4 minutes of viewing, the induced heterophoria was reduced to the baseline value. Vergence adaptation has also been reported with positive and negative lenses (North & Henson, 1985). Fixation disparity techniques have also been used to demonstrate vergence adaptation. The y intercept (fixation disparity) of the forced fixation disparity curve has been shown to return to the baseline value when binocular vision is sustained through the prism (Ogle et al., 1967) resulting in an accurate vergence response. This is supported by the finding that high levels of vergence adaptation were associated with low values of fixation disparity in the same direction (Schor, 1980).

Neurophysiological studies of phoria adaptation in monkeys showed that the majority of midbrain vergence cells decrease their firing rate for a given vergence angle following adaptation (Mays & Tello., 1986; Morley et al., 1992). Only a minority of cells (30%) had similar firing

rates before and after prism adaptation (Morley et al., 1992) showing that not all vergence cells carry a signal for adaptation.

### **1.3.2 Vergence adaptation and Cross-link magnitudes**

It has been suggested that the crosslinks receive their input from the phasic control elements (Schor, 1983b; Schor & Kotulak, 1986; Schor, 1992) and that the magnitude of the crosslink is directly proportional to the fast component output and is inversely proportional to the slow component output (Schor, 1986). With adaptation, when the slow component takes over reducing the output of the fast component, the crosslink driven by the fast component is reduced (Schor, 1983b; Schor, 1992). Supporting this view, VA and AV have been shown to be inversely related to the adaptability of vergence and accommodation systems respectively. Accordingly, the amplitude of CA/C ratio is found to be inversely proportional to the degree of vergence adaptation. A similar relation exists between AC/A ratio and accommodative adaptation (Schor, 1988; Schor & Horner., 1989; Schor, 1992).

In this thesis, only horizontal prism adaptation in the Base-Out (BO) direction is considered.

## **1.4 Vergence Adaptation, Non-Strabismic Binocular Motor Deficiency and Positive Fusional Vergence Training**

### **1.4.1 Vergence adaptation in binocular motor deficiencies**

It is critical for the slow fusional vergence mechanism to replace much of the fast fusional vergence response over time for comfortable prolonged viewing and to relieve the stress upon the fast fusional vergence mechanism (Schor, 1979). For individuals with a deficient slow vergence mechanism, the fast fusional controller maintains the vergence response forcefully and this excessive demand placed upon the fast component can result in asthenopia (Rosenfield et al., 1994). North and Henson (1981) studied the magnitude of prism adaptation in individuals with abnormal binocular vision or asthenopia. They found that the symptomatic subjects exhibited reduced magnitude of adaptation horizontally but demonstrated normal vertical prism adaptation. Also they reported that vergence adaptation is more defective at the distance where the symptoms were severe. Neurophysiological evidence shows defective or absent prism adaptation in monkeys having cerebellar lesions involving dorsal paraflocculus and uvula regions that receive mossy fiber visual error signal (Baizer et al., 1999).

### **1.4.2 Normalizing vergence adaptation with positive fusional vergence training**

The current naturalistic visual demands require prolonged periods of near fixation necessitating accurate vergence and accommodative responses. As noted previously, defective slow fusional vergence mechanism produces asthenopic symptoms. Literature evidence suggests that the slow fusional vergence mechanism is amenable to training to restore normalcy resulting in alleviation of near visual symptoms (Brautaset & Jennings., 2006). The ability of the oculomotor system to

adapt to prism induced heterophoria was evaluated before and after orthoptic treatment in a group of convergence insufficiency subjects. The results showed improvement in the subjects' ability to adapt to prism associated with ameliorated symptoms (North & Henson., 1982 & 1992). From the current models, this improved ability of the vergence system to adapt following fusional vergence training is predicted to modify the cross-link ratios. Although a few studies showed the possibility of the change in the ratios (Flom, 1959; Manas, 1958; Hung et al., 1986), a recent study did not show a significant alteration with training (Brautaset & Jennings., 2006). The mechanism of vergence adaptation influencing the cross-link ratios is not clearly understood due to this controversy.

This main objective of this thesis is to study the effect of vergence adaptation and its training on the critical oculomotor parameters.



## Chapter 2 RATIONALE FOR THE STUDY

It is apparent from the literature review section that there exists controversy regarding the mechanism of vergence adaptation influencing the CA crosslink. Universally, positive fusional vergence training has been shown to improve near vision symptoms resulting in enhanced positive fusional amplitude (Cooper et al., 1983; Brautaset & Jennings., 2006). Studies have shown that the static values of the cross-link ratios do not change significantly with positive fusional vergence training that appears to improve the vergence adaptation (Brautaset & Jennings., 2006). The underlying basic mechanism that alters with training resulting in improved BO fusional amplitude is not clearly understood. This thesis aims at working on the above issues in order to improve the current understanding of the accommodation-vergence interaction mechanism. Two studies were designed focusing on vergence adaptation and its relationship with Positive Fusional Vergence (PFV) training. In the first study, the effect of vergence adaptation on the CA cross-link response was evaluated to verify the placement of the CA cross-link in the currently used models. Experiments were designed to test whether the CA response is altered by vergence adaptation or not and whether the reduced CA with vergence adaptation is reflected in the post vergence adaptation open-loop accommodative response or not. In the second study, we hypothesized that the improved vergence adaptation following training would not alter the cross-link ratios, but would be manifested in the cross-link response measured dynamically over time. Accordingly, vergence adaptation was trained and the critical parameters such as the cross-link ratios, PFV amplitude were compared before and after training. Also, cross-link ratios and BO to blur value were measured under vergence adapted state to compare the values with pre and post training measures.

## Chapter 3 VERGENCE ADAPTATION REDUCES CONVERGENCE ACCOMMODATION AND CA DOES NOT INITIATE ACCOMMODATIVE ADAPTATION

### 3.1 Abstract

This study investigated the effect of vergence adaptation on the convergence accommodation (CA) response as a function of vergence stimulus magnitude and duration. Convergence was induced using no prism, 6, and 12 prism dioptres as stimuli at 0.4m, viewed for 5, 10 & 15 minutes of duration in randomized separate sessions. The effect of both magnitude and duration was tested in 6 emmetropes. Since the results showed no significant differences in the durations selected, the effect of magnitude alone was tested in 4 more emmetropes. Phoria measures and CA responses were recorded at the baseline, immediately following prism insertion and following specific durations of viewing through the prism (post-task). Repeated measures of ANOVA showed no significant ( $p > 0.05$ ) phoria adaptation or CA response change with no prism as the stimulus. For 6 and 12 prism dioptres, there were significant reductions ( $p < 0.01$ ) in CA with phoria adaptation. There was a significant difference ( $p < 0.01$ ) between the baseline and post-task measures of both CA and phoria showing incomplete adaptation. The amount of CA reduction and phoria adaptation increased with increased vergence stimulus magnitude ( $r = 0.99$ ). No significant ( $p > 0.05$ ) phoria adaptation or reduction in the CA response between 5, 10 and 15 minutes of viewing showing no effect of duration. Also the effect of CA cross-link on the tonic accommodation (TA) adaptation was investigated where TA response was measured before and after the convergence task. Statistical analysis showed no significant difference ( $p = 0.85$ ) between the pre and post task TA response while vergence was adapted. Thus results of the study

show that vergence adaptation reduces CA response supporting models which predict the CA crosslink to reduce its output as tonic vergence adaptation progresses. However the convergence accommodation does not appear to lead to increased output of tonic accommodation.

Keywords: convergence accommodation (CA), vergence adaptation, tonic accommodation (TA)

### 3.2 Introduction

The Maddox's (Maddox, 1886) hierarchy of vergence did not identify the existence of two other mechanisms; namely, the convergence accommodation and the vergence adaptation. Under natural viewing conditions, vergence and accommodation interact with each other via the two neural cross-links, convergence accommodation (CA) (Fincham & Walton., 1957; Kent, 1958; Morgan, 1968) and accommodative convergence (AC) (Morgan, 1944; Alpern et al., 1959). The magnitude of CA is usually measured under open-loop of accommodation condition where negative feedback loop of accommodation is disabled by removing the blur stimulus to accommodation. Studies done in the past used 0.5mm diameter pinholes (Rosenfield & Gilmartin, 1988) or a 0.2cpd difference of Gaussian target (Kotulak & Schor, 1987) to open the accommodation feedback loop while measuring the CA response. The slope of the linear fit plotting the induced convergence in meter angles (MA) and the resulting change in the accommodative response will give the stimulus convergence accommodation to convergence ratio (sCA/C). In young adults, CA/C ratio was found to be as high as 1 D / MA of convergence (Fincham & Walton, 1957) although a range from 0.3 to 0.6 D / MA of convergence has been reported in other studies. Similarly, AC magnitude is measured under open-loop of vergence.

Maddox's classification served as a basic step in the modeling of the vergence system. Several mathematical models have been developed to explain the underlying mechanism of accommodation and vergence and their interaction. The basic configuration of the model is a negative feedback control to ensure the output of the system is attained and maintained to a desired value while the external environment is varying. Based on the placement of the cross-

links in the feed forward loop, different accommodation-vergence interaction models have been developed. The vergence model is comprised of the following elements Disparity vergence which is clinically referred to as fusional vergence, consists of two components, a fast component and a slow component (Schor, 1979), CA cross-link that feeds into the accommodation system, and a tonic vergence that reflects the baseline innervation to the extraocular muscles. An analogous system is present for accommodation which is interlinked with vergence through the AC cross-link. For the purpose of this paper, only the vergence system is described. There exists a controversy in the currently used accommodation-vergence interaction models due to the placement of the cross-link components in the model. According to Schor's model (Schor, 1992), the cross-links are placed in between the fast and the slow components. This is in contrast to the model proposed by Ebenholtz & Fisher (1982) in which the crosslinks are placed after the slow component. This issue has been addressed in the current study to evaluate the possible placement of the crosslinks in the model.

Like any other biological system, the oculomotor system does exhibit the ability to adapt to the changes in the environmental conditions. Adaptation is a property which is required in order to coordinate between the system's existing level of action and the ongoing stimulus demand from the environment which then allows a stability required for sustained comfortable viewing. Vergence adaptation is best illustrated by presenting a disparity to the eyes by means of an ophthalmic prism that induces a change to the heterophoria. The resulting fusional vergence aligns the visual axes to fixate at the same point of regard to render fusion. When binocular vision is sustained through the prism, the induced heterophoria reduces towards the initial

baseline phoria value. Such an adaptive modification of the vergence system has been demonstrated by previous studies that induced changes in the heterophoria by introducing prisms (horizontal and vertical) (Henson & North, 1980; North & Henson, 1992) and positive or negative lenses (North & Henson, 1985). These authors found that the heterophoria induced using 6Δ BO in normal individuals reverted back to the baseline value within 3 to 4 minutes of binocular viewing showing the vergence system's adapting ability (Henson & North, 1980). Also it has been shown that subjects who experienced asthenopic symptoms showed poor or absent prism adaptation (North & Henson, 1981) and the adaptation ability improved following orthoptic training (North & Henson, 1992).

The fast (reflex or phasic) fusional vergence component responds rapidly (within a second) to reduce the retinal disparity and the slow (adaptive or tonic) fusional vergence component maintains the net fusional vergence response (Schor, 1979) upon sustained fixation. Since the system operates under a negative feedback mechanism, the onset of slow fusional vergence response reduces the output of the fast fusional vergence component to maintain the aggregate vergence response. Following sustained vergence task, and upon removal of the vergence stimulus, the output of fast component dissipates rapidly in contrast to the slow adaptive component which exhibits slower rate of decay of its response. It has been suggested that the open-loop vergence response following sustained vergence task is a composite of underlying tonic vergence and the sustained output of slow fusional vergence since no experimental evidence suggested any change in the baseline tonic innervation (Rosenfield, 1997). This apparent increase in the tonic vergence response reflecting the slowly decaying slow component

response (Schor, 1979; Rosenfield & Gilmartin, 1989) is referred to as the vergence adaptation (Sethi, 1986). It is therefore necessary to differentiate slow fusional output from the tonic vergence output. Tonic vergence gives a constant output. It is only the slow component that adapts and is measured along with the tonic vergence since the net response contains input from both tonic and slow components.

Schor's model of accommodation-vergence interaction (Schor, 1983a) suggests that the output of the fast (phasic) component serves as the input to the slow (tonic) component and that the cross-links receive input from the phasic control elements (Schor, 1983b; Schor & Kotulak, 1986; Schor, 1992) and the magnitude of crosslink is directly proportional to the fast component output and is inversely proportional to the slow component output (Schor, 1986). With adaptation, when the slow component takes over reducing the output of the fast component, the crosslink driven by the fast component reduces (Schor, 1983b; Schor, 1992). Evidence to support this view comes from the study in which the vergence accommodation and accommodative vergence have been shown to be inversely related to the adaptability of vergence and accommodation systems respectively. Accordingly, the amplitude of the CA/C ratio was found to be inversely proportional to the degree of vergence adaptation. A similar relation existed between AC/A ratio and accommodative adaptation (Schor, 1988; Schor & Horner., 1989; Schor, 1992). This is contradicted in the study where CA response was measured over a period of 3 minutes of viewing through 0 & 6 Δ under open-looped accommodation and the results showed no reduction in the CA response over the course of 3 minutes viewing, suggesting that the CA is driven by both the fast (initially) and slow (subsequently) components (Rosenfield & Gilmartin,

1988). This finding supports the accommodation-vergence interaction model proposed by Ebenholtz & Fisher (1982) in which the tonic components are placed prior to the cross-links in the feed forward loop. The results were supported by Hung (1992) from his model stating the constancy of CA following vergence adaptation. Lakkis and Bruce (1989), on their comments to the experimental results given by Rosenfield & Gilmartin (1988), have suggested that the constancy of CA response with vergence adaptation could be due to the slowly decaying TA that had adapted to the initial CA that fed into accommodation system. The constancy of the CA response following prism adaptation was also supported by Schor (1992) from his model in which the cross-links feed into the opposite systems' adapting element. It was suggested that CA driven by the prism insertion initiates tonic accommodation adaptation and the response is stored in the accommodation system. Since the net accommodative response measured during open-looped accommodation consists of both CA and TA outputs, there will not be a significant reduction in the net accommodative response following phoria adaptation, although vergence adaptation reduces CA (Schor, 1992).

The purpose of this study was to evaluate the effect of vergence adapted to different stimuli under different durations of viewing on the CA response. Since magnitude of the adapting vergence stimulus has been shown to influence the vergence adaptation directly (Sethi & North., 1987) and also duration of the adapting stimulus is directly related to the magnitude of vergence adaptation (Fisher et al., 1990), we hypothesized that the vergence adapting to higher magnitude and longer duration of stimulus could reduce CA response significantly. Also the CA cross-link initiating accommodative adaptation was verified to evaluate whether the reduced CA following



vergence adaptation is reflected in the open-loop accommodative response measured following vergence adaptation or not. Also empirical results were simulated using Schor's model in the MATLAB Simulink program and the model predictions were cross verified. Simulation results are discussed in section 5.4.1 of appendix IV.

### **3.3 Methods & Materials**

The study was approved and received the complete ethics clearance from the Office of Research Ethics at the University of Waterloo.

#### **3.3.1 Instrumentation**

Accommodative responses (AR) were measured using the commercial Power Refractor (MultiChannel Systems, Reutlingen, Germany). Individual calibration was carried out and the calibration results are summarized in appendix B. The Power refractor is an infra-red optometer that works on the principle of eccentric photorefracton (Schaeffel, 1993; Howland, 1985; Bobier & Braddick., 1985). In eccentric photo refraction, an infra-red flash source placed eccentric to the aperture of the camera lens is reflected from the eye and creates an intensity profile along the vertical meridian of the pupil. The accommodation response output given by the instrument is calculated by substituting the slope of the brightness profile across the pupil using an inbuilt equation of the instrument (Schaeffel, 1993). The sampling rate of the instrument is 25Hz which allows it to take fast measurements. The instrument works at a distance of 1m. In the current investigation, measures were taken using the binocular mode with gaze control set to 30° for 5 seconds. The mode provides measures of the accommodative response along the vertical meridian along with the pupil diameter and gaze shifts. Binocular mode tracks vergence while

subjects view the target through a horizontal prism. In the current investigation, the vergence stimulus in the form of Base-Out (BO) prism was placed in front of the left eye. Fusion through the prism was ensured from symmetrical Hirschberg images from both the eyes. When BO prism was placed in front of the left eye, it initiates a yoked saccadic movement towards the right side (dextroversion). The Hirschberg images become asymmetrical. To regain fusion, the right eye makes a convergent movement and the resultant is a symmetrical corneal reflex as viewed through the prism (Alpern, 1969; Bobier et al., 2000). All the accommodative responses were measured when fusion was reported by the participants. Although binocular accommodative response was obtained, only measures from the right eye (averaged from 5 seconds data) were used for analysis purposes.

Heterophoria measures were taken using the modified Thorington technique (MTT) (Borish, 2006). The magnitude of the phoria was quantified using a custom made tangent scale whose validity and repeatability was evaluated at 0.4m (Results are summarized in appendix C). The scale consisted of a central fixation light with letters on the right side and numbers on the left side. The letters and numbers were spaced 4mm apart to represent 1  $\Delta$  of displacement at 0.4m. The magnitude and direction of the horizontal phoria was determined in the following manner. Participants were instructed to fixate at the central fixation light of the tangent scale. An occluder was placed in front of the right eye for 10seconds and the Maddox rod was inserted with the occluder in place. 10 seconds of occlusion would allow fast fusional component to decay. Following 10 seconds of occlusion, the occluder was removed and the participants were asked to report the number or the alphabet letter on which the red vertical streak fall immediately

following eye opening. The displacement of the streak on numbers denotes exophoria and on letters denotes esophoria. The above procedure was repeated thrice and averaged as the phoria value.

### **3.3.2 Experiment (a) Vergence adaptation as a function of stimulus magnitude and duration**

The purpose of this experiment was to evaluate the effect of vergence adaptation on the CA response using 3 different magnitudes and 3 different durations of adapting stimulus.

#### **Study Participants**

10 healthy emmetropic adults, between the ages of 23 and 30 years (mean age  $26 \pm 2.91$  years) from the student population of School of Optometry at the University of Waterloo participated in this study. 6 individuals participated in both the magnitude and duration experiment. Since the results showed no effect of duration on phoria adaptation, the effect of magnitude alone was tested in 4 more emmetropes. Testing was conducted after obtaining informed consent from the participants. All participants underwent a screening test to determine refraction and binocular status. Participants had visual acuity of at least 6/6 in each eye, normal distance and near heterophoria (using modified Thorington method) and normal distance and near positive fusional amplitudes based on Morgan's criteria (Morgan, 1944) and normal near point of convergence (Scheiman & Wick., 2002, page no.9). The Stimulus CA/C ratio was measured inducing 0, 3, 6, 9, & 12  $\Delta$  BO in the left eye and the concomitant change in the open-loop accommodative response (CA) was measured from the right eye at 0.4m. The mean CA/C ratio for all the participants at 0.4m was found to be 0.81D/1MA of convergence.

## **Experimental Target**

In order to measure a true CA response, it is necessary to disable the accommodation negative feedback loop by removing the blur stimulus to accommodation. Therefore any change in the accommodative response resulting from the induced convergence can be denoted as the change due to CA (assuming proximal and tonic accommodation responses to be constant). A difference of Gaussian (DoG) target whose spatial frequency is less than 0.5 cycles/degree has been shown to be a poor stimulus to stimulate reflex accommodation (Kotulak & Schor., 1987) and has been used in several studies to measure CA (Tsuetaki & Schor., 1987; Suryakumar & Bobier., 2004). In the current study, a DoG target whose spatial frequency was 0.2 cycles/ degree at 0.4m was generated using MATLAB, validated and was used to open the loop of accommodation. (Refer to appendix A for validation of DoG stimulus). The target was displayed from a laptop to a miniature 1.77" LCD monitor placed at a distance of 0.4m from the subject and was projected on to a semisilvered mirror placed in front of the subject.

## **Experimental Procedure**

The experimental procedure consisted of total of 9 sessions involving vergence adaptation under open-looped accommodation at 0.4m with three magnitudes of vergence stimuli, no prism, 6 $\Delta$  and 12  $\Delta$  BO and under three different durations, 5, 10 and 15 minutes of viewing, in separate randomized experimental sessions separated from each other by at least 24 hours to minimize the effects of the previous session's vergence adaptation on the responses. 6 emmetropes took part in the testing. During each session, subjects sat in the dark for 5 minutes to avoid the previous near task's influence (Wolf et al., 1987). All participants were seated comfortably with their head

positioned in the chin/head rest assembly to ensure constant fixation distance throughout the duration of the study. Subjects used the principle of physiological diplopia to adjust the position of the semisilvered mirror upon which the DoG target was projected and this ensured that the target evoked close to symmetric convergence. Baseline measures of near heterophoria were taken. Subjects then fixated the central bright band of the DoG target while the baseline CA response was measured for 5 seconds using binocular mode in power refractor. This was followed by the insertion of the vergence stimulus (no  $\Delta$  / 6  $\Delta$  / 12  $\Delta$ ) in front of the left eye. For no  $\Delta$  as stimulus, an empty cell (used for holding the prisms) was introduced. Phoria and the accommodative response immediately following the introduction of vergence stimulus were recorded. Subjects were then allowed binocular viewing through the vergence stimulus for a specified duration (5/ 10/ 15 minutes). Upon completion of specific duration of binocular viewing through the prism, post vergence task accommodative response and phoria were measured with adapting stimulus in place. To avoid erroneous results, blink artifacts were reduced by removing 1 data point before and 1 after the blink. For a particular time point, the accommodative response was an average of the data points retained after removal of blink artifacts. The criterion used for removing the blink artifacts has been used in previous studies (Allen et al., 2003; Sreenivasan, 2007). The session was repeated with other magnitudes and durations of vergence stimulus. Phoria measures and accommodative responses were analyzed using repeated measures ANOVA to evaluate the effect of stimulus magnitude and duration. As mentioned earlier, since the results showed no effect of duration on phoria adaptation and CA response change in 6 participants, the effect of stimulus magnitude alone was tested in 4 more emmetropes. The experimental procedure consisted of 3 sessions involving measurement of

accommodative and phoria responses during vergence adaptation with three magnitudes of vergence stimuli, no prism, 6 $\Delta$  and 12  $\Delta$  BO. Each stimulus was viewed for only 5 minutes of duration in separate randomized experimental sessions.

### **3.3.3 Experiment (b) Effects of CA cross-link stimulation on accommodative adaptation**

The purpose of this experiment was to evaluate the influence of CA stimulation on accommodative adaptation under open-looped accommodation.

#### **Experimental Target & Study Participants**

The accommodative loop was opened using a DoG stimulus whose spatial frequency was 0.18 c/deg at 3.5m. Ten emmetropic adults that participated in experiment (a) served as the subjects.

#### **Experimental Procedure**

Participants initially sat in the dark for 5 minutes to avoid the influence of possible previous near tasks on the responses. Participants fixated at the central bright band of the DoG target at 3.5m with the right eye while the left eye was occluded. Dual open-loop AR from the right eye was measured using the fast screening mode of the power refractor and 3 consistent responses were averaged to give pre-task TA response. The occluder was removed from the left eye and the baseline CA was measured from the right eye. Convergence was induced using 12  $\Delta$  BO in front of the left eye while the participants fixated the DoG at 3.5m. The concomitant change in the AR resulting from convergence (CA) was measured from the right eye. Participants sustained binocular fixation through the prism for 5 minutes while fixating at the DoG. Upon completion of 5 minutes of viewing, open-loop AR was measured. The left eye was then occluded for 10-15 seconds to decay the fast vergence component output. Immediately after this the monocular open-loop AR response was measured from the right eye which denoted the post-task TA response.

## **3.4 Results**

### **3.4.1 Experiment (a) Effect of stimulus magnitude and duration on vergence adaptation and CA response**

Phoria and CA measures taken during all sessions were analyzed using repeated measures of ANOVA with STATISTICA software to evaluate the effect of magnitude and duration on the phoria and CA responses.



### Effect of vergence stimulus duration on phoria adaptation and CA reduction

There was no significant difference ( $F = 0.495$ ,  $p = 0.852$ ) in the phoria adaptation between 5, 10, & 15 minutes of viewing across all three magnitudes of vergence stimuli as seen from figure 3.1.

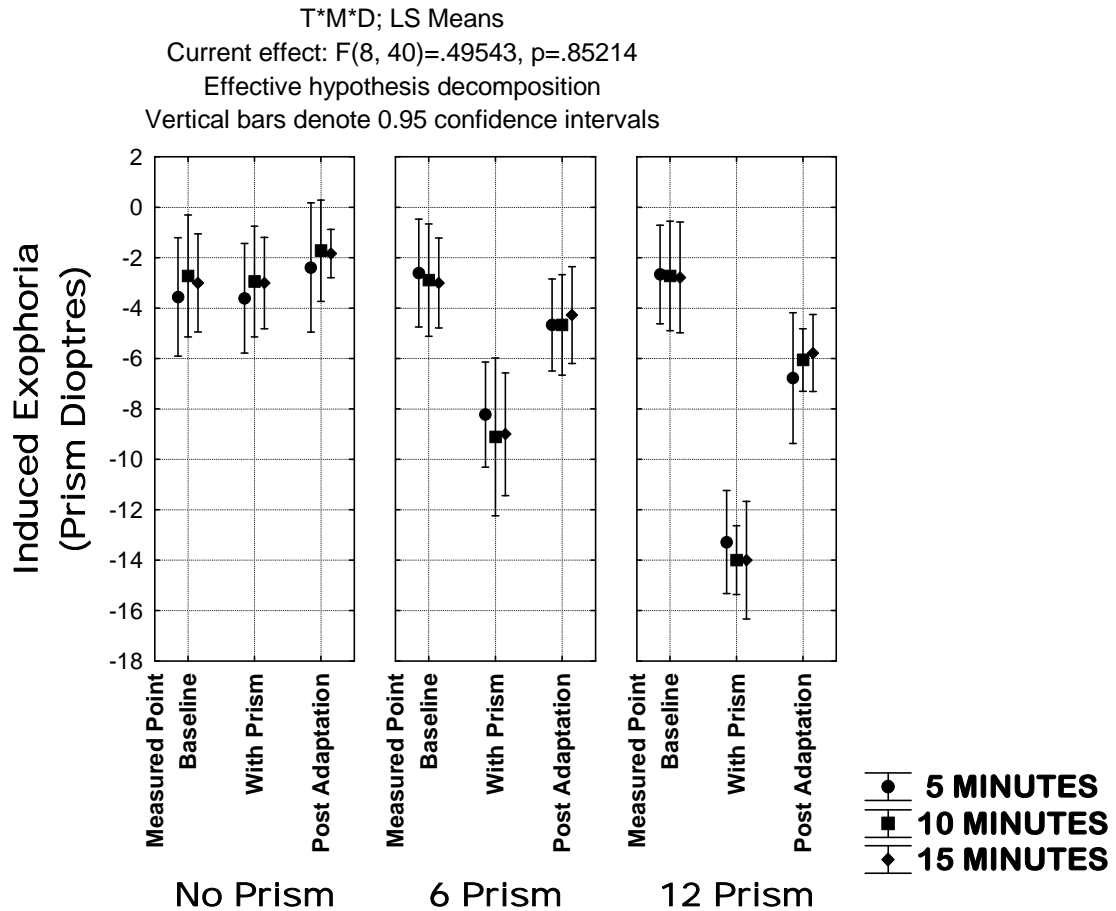


Figure 3.1 illustrating no phoria adaptation for all three durations of viewing with no prism. Similar amounts of phoria adaptation under all three durations of viewing for 6 & 12 prisms showing no effect of duration on phoria adaptation (Error bars indicate  $\pm 1SE$ ).

Similar results were obtained for CA responses showing no significant difference ( $F=0.71$ ,  $p = 0.675$ ) in the CA response reduction between 5, 10 & 15 minutes for all three magnitudes of stimulus. This is depicted in figure 3.2.

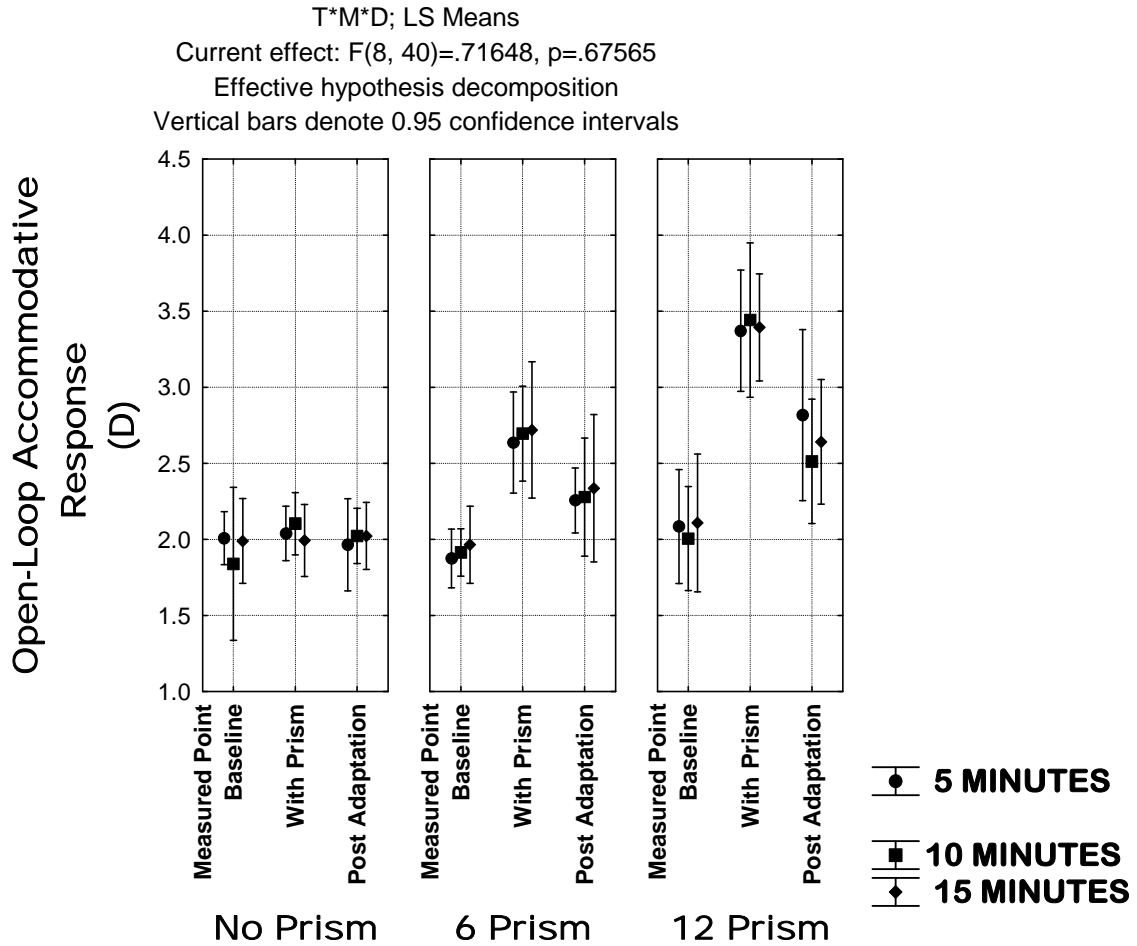
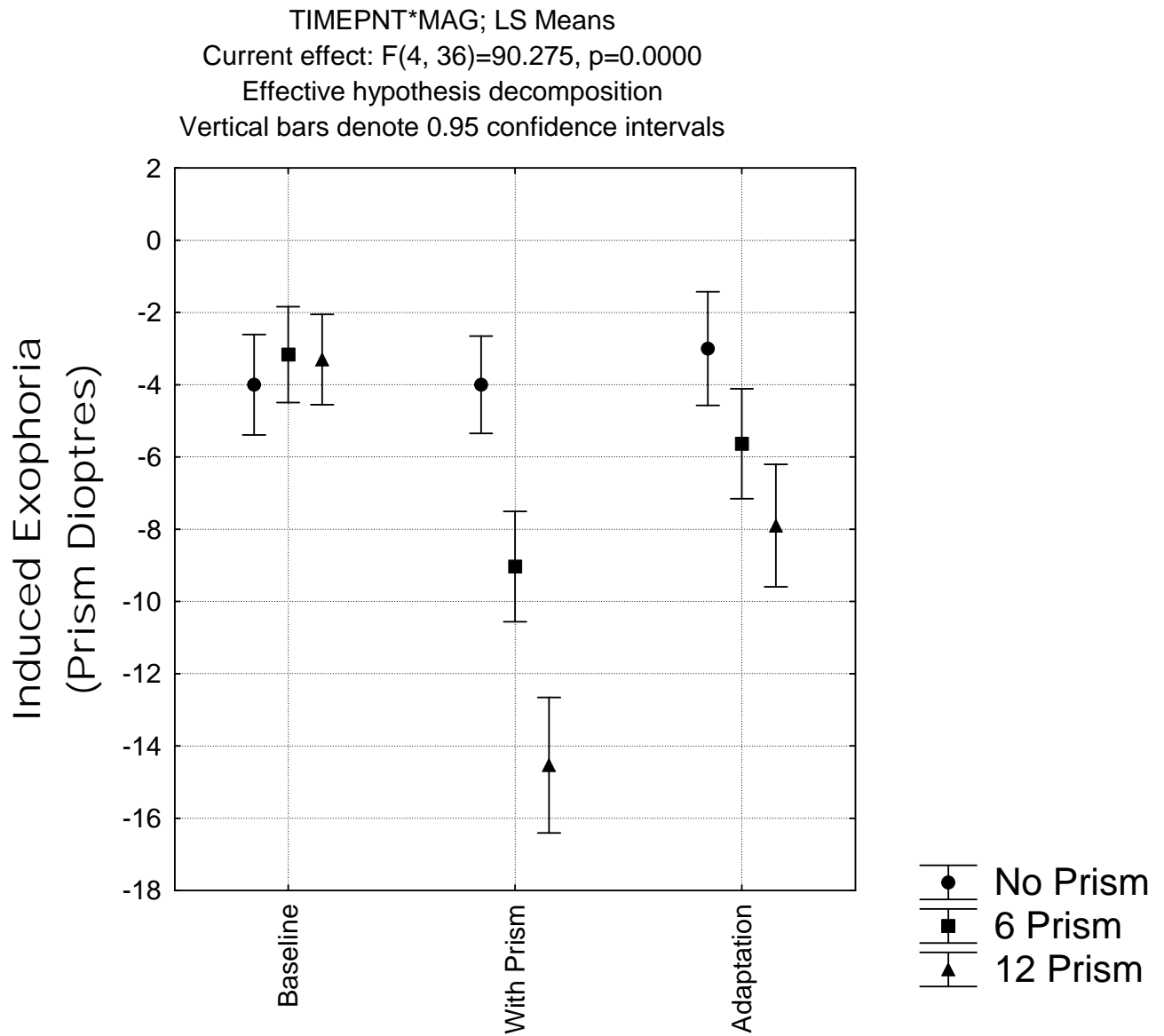


Figure 3.2 illustrating no CA response reduction for all three durations of viewing with no prism. Similar amounts of CA response reduction under all three durations of viewing for 6 & 12 prism stimuli showing no effect of duration on CA response reduction (Error bars indicate  $\pm 1SE$ ).

### **Effect of vergence stimulus magnitude on phoria adaptation and CA response**

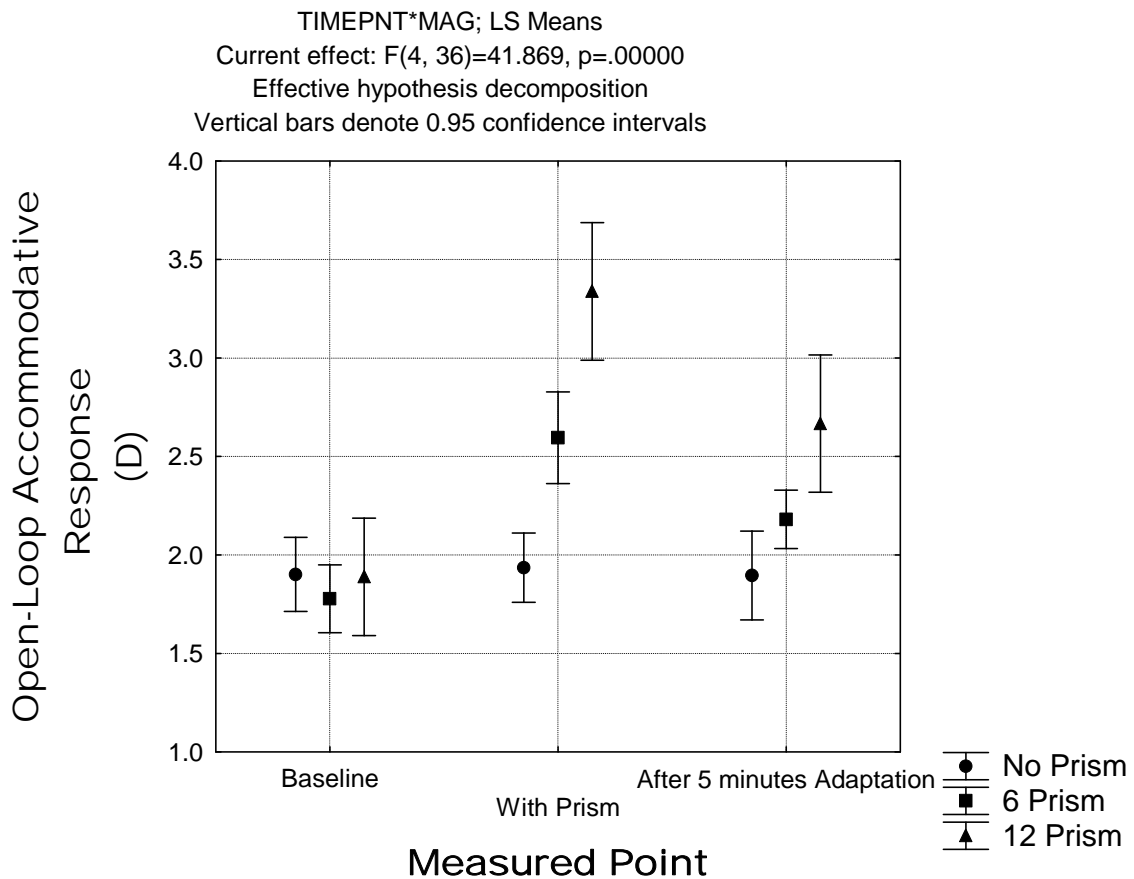
The results showed to explain the effect of magnitude consists of data from 10 emmetropes tested for 5 minutes of stimulus duration

At 0.4m, with no prism ( $0\Delta$  induced heterophoria), there was no significant phoria adaptation ( $p=0.76$ ). For 6 & 12  $\Delta$  vergence demands, the exophoria increased significantly ( $p = 0.0005$ ) from the baseline following BO prism insertion as expected. The post-task exophoria following 5 minutes of viewing through the prism decreased significantly ( $p = 0.001$ ) from the induced heterophoria denoting prism adaptation. But it did not reduce completely to the baseline phoria value and was significantly different ( $p =0.001$ ) from the baseline phoria measure as shown in figure 3.3.



**Figure 3.3** The mean exophoria is shown in pre test condition and then immediately upon prism insertion (0, 6 or 12) followed by 5 minutes of prism viewing. Phoria adaptation is defined as the prismatic difference between prism insertion and 5 minutes of viewing. At 0.4m, no adaptation for no  $\Delta$  and significant adaptation for 6 and 12  $\Delta$ s for 5 minutes of stimulus duration (Error bars indicate  $\pm 1SE$ ).

A similar trend was seen for CA responses where CA response increased significantly ( $p = 0.004$ ) from the baseline value following prism insertion. Following the adaptation period (5 minutes viewing through the prism), the CA response decreased significantly ( $p = 0.0001$ ), but did not reduce completely to the baseline value. The post-task CA response remained significantly different ( $p = 0.001$ ) from the baseline CA response. For no prism as the stimulus, there was no significant difference ( $p = 0.76$ ) in the CA response following 5 minutes of viewing as shown in figure 3.4.



**Figure 3.4 showing the effect of stimulus magnitude on CA response reduction with phoria adaptation. At 0.4m, no reduction for no  $\Delta$  and significant reduction for 6 and 12  $\Delta$ s for 5 minutes of stimulus duration (Error bars indicate  $\pm 1SE$ ).**

It can be inferred from figures 3.3 & 3.4 that the highest magnitude of vergence demand ( $12\Delta$ ) produced the greatest amount of phoria adaptation and the greatest reduction of CA response when compared to the  $6\Delta$  vergence demand showing an effect of vergence stimulus magnitude on adaptation. The amounts of phoria adaptation and CA reduction were found to be positively correlated ( $r = 0.99$ ) with the magnitude of vergence stimulus demand.

### 3.4.2 Experiment (b) Effects of CA cross-link stimulation on tonic accommodation adaptation under open-looped accommodation

The CA responses at baseline, immediately following 12 Δ insertion and following 5 minutes of adaptation were analyzed using repeated measures of ANOVA. Results show that the CA increased significantly ( $p=0.002$ ) from the baseline following prism insertion as would be expected. Following 5 minutes of adaptation, the CA response decreased significantly ( $p=0.005$ ) from the value that was found immediately with prism. The post adaptation CA response was found not to be significantly different ( $p=0.836$ ) from the baseline measure showing complete reduction of CA following prism adaptation at 3.5m. This is illustrated in figure 3.5.

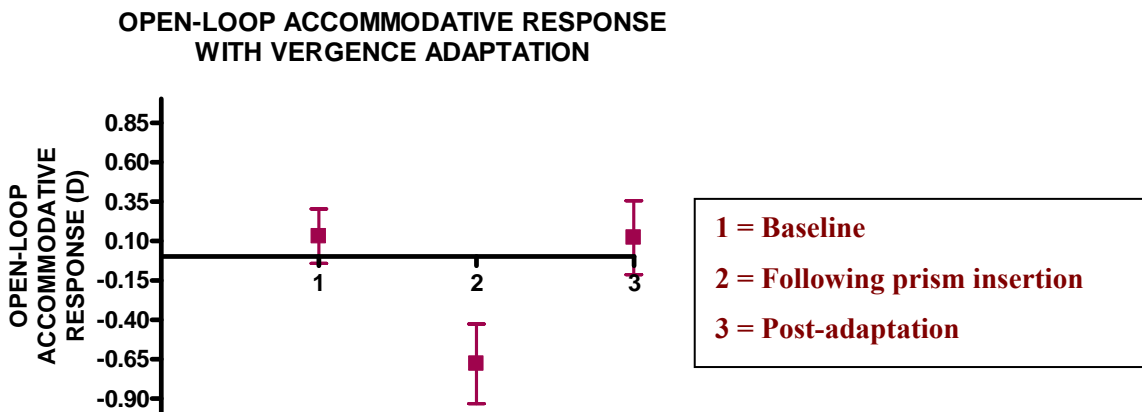
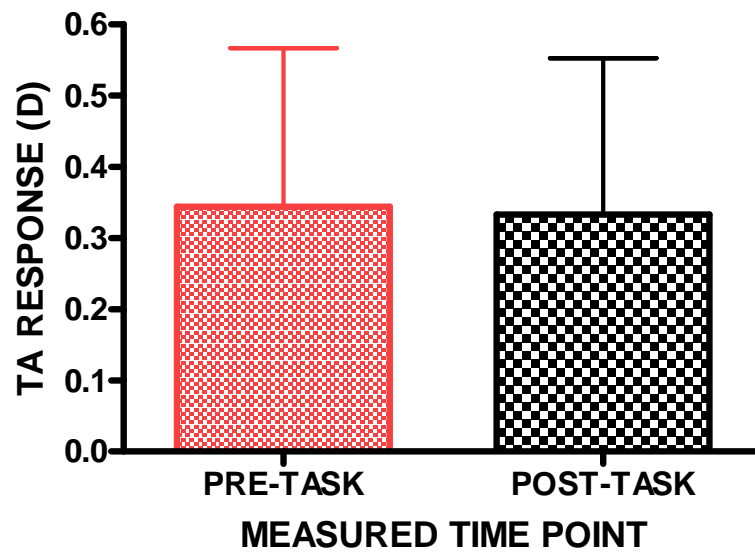


Figure 3.5 showing increase in the CA response following 12Δ BO insertion and decrease in the response following 5 minutes of viewing at 3.5m and is not significantly different from the baseline value demonstrating prism adaptation (Error bars indicate  $\pm 1SE$ ).

Pre and post-task TA measures were analyzed using paired 't' test to evaluate the effect of CA on the TA response. The results showed no significant difference ( $p=0.85$ ) in the TA response between pre and post vergence adaptation indicating no tonic accommodative adaptation as shown in figure 3.6.



**Figure 3.6 showing no difference in the pre and post task TA response following vergence adaptation (Error bars indicate  $\pm 1SE$ ).**

Simulation results are discussed in appendix D.



### 3.5 Discussion & Conclusions

While studies on vergence adaptation are well established, the effect of adaptation on the cross-link output was not clearly understood. The controversy that exists concerning the adaptation mechanism influencing its respective cross-link magnitude is attributed to the placement of these cross-link components in the feed forward loop of different accommodation-vergence interaction control models based on the empirical studies. In the experiment (a), at 0.4m, with no prism in place, no significant phoria adaptation was found. And no corresponding reduction in the CA response resulted. Exophoria and CA responses were found to increase significantly from the baseline value following the insertion of 6 and 12  $\Delta$  as would be expected. The increase in the CA response was related to the subjects' CA/C ratio. For both 6 and 12  $\Delta$  vergence demands, exophoria and CA reduced significantly following 5 minutes of adaptation. However, there was no significant difference in the phoria adaptation or CA response reduction between 5, 10 and 15 minutes of viewing showing no effect of stimulus duration on the phoria adaptation and CA response reduction beyond 5 minutes of viewing. There could be a possibility that the adaptation was affected by the duration when it was less than 5 minutes (Fisher et al., 1990).

The magnitude of the vergence stimulus is shown to affect the amount of prism adaptation and CA response reduction directly. The amounts of prism adaptation and the reduction in the CA response were positively correlated with the magnitude of the vergence demand. With an increase in the stimulus magnitude, there was an increase in the initial convergence accommodation which was followed by an increase in the amount of phoria adaptation and greater reduction in the CA response. The results clearly demonstrate reduction in the CA

response with vergence adaptation. Using Simulink (Mathworks, USA) (appendix 4) we have verified the empirical results using Schor's model.

The second experiment in this study was done to verify whether the CA cross-link initiates accommodative adaptation or not. The apparent post-task shift in the TA response relative to the pre-task level demonstrating prolonged decay of the slow component of blur driven accommodation has been defined as the accommodative adaptation (Rosenfield, 1994). If the CA that was induced with 12  $\Delta$ , in the experiment (b) of the current study, had initiated the accommodative adaptation, post-vergence task TA response should have been greater than the pre task level. The results showed that there was no significant difference in the TA response between pre and post vergence adaptation indicating no significant accommodative adaptation. Thus the results do not support the view that the CA cross-link initiates adaptation of the accommodative system. However, the CA response reduced significantly following 5 minutes of prism adaptation and the post task CA was not significantly different from the baseline value showing complete adaptation at 3.5m.

The results of this study support Schor's model of accommodation-vergence interaction in which the cross-links originate between the fast and the slow component and the magnitude of the cross-link reduces when the output of the fast component is reduced with adaptation which feeds into the cross-link. This reduction in the CA response is reflected in the open-loop accommodative response that is measured following vergence adaptation. However, the results do not support the view that CA cross-link induces accommodative adaptation which is in

contrast to Schor's model. Also the results are not consistent with the previous findings in which the accommodative adaptation was reported with convergent stimulus (Schor et al., 1986; Schor & Kotulak., 1986) under open looped accommodation. The current study results can be justified as follows. There could be a possibility that the cross-link does not feed into the adapting element of the opposite system but feeds into the summing junction. In this study, the post-vergence task TA was measured following 10-15 seconds of occlusion of the left eye to allow for fast fusional vergence decay. Previous studies have reported rapid regression of post-task TA to the baseline in emmetropes (Strang et al., 1994; Gilmartin & Bullimore., 1991). Since the current study involved emmetropes, there could be a possibility that the induced accommodative adaptation decayed rapidly before the post task TA was measured. However, if accommodative adaptation had occurred, open-loop accommodative response following vergence adaptation would not have reduced. Since the study results demonstrated a reduction in the CA response following 5 minutes of viewing through the prism at 3.5m, accommodative adaptation did not take place. The other possibility could be the fact that the accommodation system does not adapt significantly to the vergence stimulus when compared to the adaptation that is induced by an equivalent dioptric stimulus. This leads us to a question whether accommodative adapting element possesses similar gain values for both blur-driven and disparity driven accommodation drive. More experiments are needed to compare the magnitude of accommodative adaptation with blur and disparity stimuli. The current study involved only the CA cross-link effect on accommodative adaptation and did not investigate the AC cross-link on the vergence adaptation. Hence there is no conclusive evidence on the cross-links not initiating opposite systems'

adaptation. However, AC cross-link inducing phoria adaptation has been reported (Gowrisankaran et al., 2007).

In conclusion, the CA response reduces with vergence adaptation and it will get reflected in the open-loop accommodative response measured following vergence adaptation since CA cross-link does not initiate accommodative adaptation. Accordingly, the CA cross-link is placed between the fast and the slow fusional vergence, but it does not feed into the adapting element of accommodation system. Clinically, positive fusional vergence training has been shown to improve vergence adaptability. However, whether this improved vergence adaptability reducing the CA response gets reflected in the static CA/C ratio is in question. Findings of Brautaset & Jennings (2006) show no change in the CA/C ratio following vergence training in convergence insufficiency cases. Increase in the BO fusional range following training could be due to the improved vergence adaptation reducing the CA response. Further experiments are required to dynamically assess CA response with vergence adaptation to give conclusive answers. This was experimentally tested and described in the following paper.

## Chapter 4 EFFECT OF VERGENCE ADAPTATION AND POSITIVE FUSIONAL VERGENCE TRAINING ON OCULOMOTOR PARAMETERS

### 4.1 Abstract

Amplitude of convergence and vergence adaptability have been shown to improve tremendously with positive fusional vergence training. Although improved convergence is reflected in the increased BO to blur and break values during positive fusional vergence amplitude testing using BO prisms, the basic underlying mechanism that is modified to cause an increase in the BO to blur value is not fully understood. The purpose of this study was to evaluate certain critical parameters of vergence and accommodation under vergence adaptation (induced with a BO  $\Delta$ ), before and after positive fusional vergence training. Eleven emmetropes with normal binocular vision participated in the study. Distance & near phoria, AC/A & CA/C ratios, & positive fusional amplitude at near were evaluated before and after two weeks of positive fusional vergence training. Phoria adaptation and CA responses were monitored every 3 minutes for 15 minutes while the subjects viewed through 12 $\Delta$  BO under open-looped accommodation at 0.4m before and after training. On a separate vergence adaptation session (before training), phoria adaptation was induced under dual closed-loop condition using 12 $\Delta$  BO at 0.4m. Cross-link ratios, BO fusional amplitude at 0.4m and near phoria were measured following 15 minutes of prism adaptation. Subjects underwent 2 weeks of positive fusional vergence training using variable tranaglyphs and aperture rule at 0.4m. Phoria adaptation and CA responses monitored over time were exponentially fit and were compared before and after training. AC/A & CA/ C ratios and BO to blur value at 0.4m taken before training, under the vergence adapted state and after training were analyzed using repeated measures ANOVA. No significant difference ( $p >$

0.05) in the cross-link ratios were found before and after training. However, there was a significant ( $p < 0.01$ ) increase and decrease in the AC/A and CA/C ratios respectively under the vergence adapted state. BO to blur value at 0.4m was significantly increased ( $p < 0.01$ ) from the pre training value under both vergence adapted condition and following training. Rate constants and magnitudes of phoria adaptation and CA response reduction were significantly ( $p < 0.01$ ) different following training demonstrating robust and greater magnitude of vergence adaptation in the BO direction reducing the CA response faster. However, this improved vergence adaptability is not reflected in the static measures of AC/A and CA/C ratios. The increased BO to blur value following training is caused by the increased speed of prism adaptation reducing the CA response during BO fusional amplitude testing.

Keywords: accommodation, accommodative convergence, convergence accommodation, vergence adaptation, cross-link ratios, positive fusional vergence training

## 4.2 Introduction

Clinically, an individual's ability to converge is determined by positive fusional vergence amplitude (Scheiman & Wick, 2002). It is usually measured by holding the accommodative stimulus constant and increasing the amount of BO prisms in front of the eyes until the subject reports blur, then further increase until the subject reports diplopia and then reduce the amount until fusion is regained. The point at which blur is reported in clinical testing is termed the limit of positive fusional vergence (Fry, 1937) and the point at which diplopia occurs defines the total amount of convergence one could exert. One of the possible mechanisms reported in the literature for blur occurring at the limits of fusional convergence is due to an excessive convergence accommodation or "lens overdrive" that is associated with a strong fusional effort (Fincham & Walton., 1957; Morgan, 1968). According to the "interactive theory" proposed by Semmlow and Heerema (1979), under normal binocular viewing conditions, an independent component called 'convergence accommodation' operates to reduce the blur induced lens drive and thereby reduce the associated accommodative vergence. It was also thought that the blur due to BO prisms could be due to an increased accommodation associated with the recruitment of accommodative convergence to aid in the fusion (Fry & Balsam., 1959; Alpern, 1969). In order to study the possible role of the accommodative convergence at the limits of fusional vergence, Semmlow and Heerema (1979) designed an experiment in which the eye movements were measured dynamically using the dynamic binocular stimulator by opening the loop of vergence at the high vergence stimulus demand at which subjects were able to maintain fusion with or without detriment to the target clarity. Their results indicated that the accommodative convergence was negative during the period of high fusional demand and thus does not aid a

maximal vergence effort, rather, it is compensating for the excessive lens drive produced by convergence accommodation. Blur occurs when this compensation is no longer adequate. Further experimental evidence to support the “lens overdrive” hypothesis comes from Semmlow and Hung (1981) who measured the static accommodative responses under closed and open-loop accommodation conditions with accommodation clamped but vergence varied. Their results showed that with increasing vergence stimulus, both closed and open-loop accommodative responses increased, but the closed-loop accommodative responses were always less than the open-loop accommodative responses. It was concluded that as the vergence drive is increased, the associated vergence accommodation tends to increase the lens accommodation. If the accommodative stimulus is held constant, the accommodative system operating through feedback will compensate for this increase in disparity induced lens drive by decreasing the blur-driven accommodation and thereby reducing the accommodative convergence (Semmlow & Hung., 1981).

When a disparity is presented to the eyes in the form of a prism, the vergence system rotates the eyes in an appropriate direction to achieve fusion and this is accomplished by the act of the fast fusional vergence mechanism. If the vergence feedback loop is opened, by occluding one eye, the fast fusional vergence response decays to the tonic value. But when the binocular viewing is sustained for longer time, say more than 1 or 2 minutes, the fast component response is replaced by the slow component response which is manifested as the change in the heterophoria towards the baseline value and has been referred to as vergence adaptation (Schor 1979). With the vergence system operating under a negative feedback mechanism, the onset of slow fusional



vergence response reduces the output of fast fusional vergence response in order to maintain the aggregate vergence response and the purpose of vergence adaptation is to reduce the load on the fast fusional vergence mechanism (Rosenfield & Gilmartin., 1988; Schor, 1983). When the fusion is broken and the feedback loop is opened, the fast fusional vergence response decays faster but the open-loop vergence response remains closer to the binocular closed-loop response for a few minutes due to prolonged decay of the slow vergence component which is reflected in the post-task increase in the tonic vergence response, although tonic vergence innervation remains constant (Rosenfield & Gilmartin, 1988). While measuring the BO vergence limit, when the slow component takes over, the relieved fast fusional vergence component can respond to the newly added BO prisms over a range of prisms until the limit is reached.

Clinically, vergence adaptation has been demonstrated as prism adaptation where an ophthalmic prism is introduced before the eyes and the heterophoria measured after a period of binocular viewing through the prism is equivalent to that of the baseline phoria that is obtained before the introduction of the prism. The way the oculomotor system adapts to the horizontal ( $6\Delta$ ) and vertical ( $2\Delta$ ) disparities was tested in normal individuals by Henson & North (1980) at both distance and near. Their results show that following 3-4 minutes of viewing, the induced heterophoria was reduced to the baseline value. Vergence adaptation has also been reported with positive and negative lenses (North & Henson, 1985).

The slow fusional vergence mechanism playing a critical role in maintaining the sustained closed-loop vergence response relieves the stress on the fast fusional vergence to render

comfortable prolonged viewing. For individuals with a deficient slow vergence mechanism, the fast fusional controller maintains the vergence response forcefully resulting in visual symptoms (North & Henson., 1981). Thus the excessive demand on the fast component results in asthenopia in individuals with deficient vergence adaptation. For example, exophores at near, who cannot compensate for their phoria using positive fusional vergence and who do not possess normal vergence adaptation mechanism, prolonged near work results in symptoms such as blurred vision, diplopia, movement of prints, headache, etc (Scheiman & Wick., 2002). Several investigations have been carried out to study the adaptability of vergence system in symptomatic individuals. Studies have shown that the symptomatic subjects demonstrate deficient prism adaptation compared to asymptomatic ones. North and Henson (1981) studied the magnitude of prism adaptation in individuals with abnormal binocular vision or asthenopia. They found that the symptomatic subjects exhibited reduced magnitude of adaptation horizontally but demonstrated normal vertical prism adaptation. Also they reported that vergence adaptation is more defective at the distance where the symptoms were severe. The study on the relationship between adaptation of accommodation and vergence and magnitude of the cross-link ratios showed that the cross-link ratios are inversely related to the adaptability of their respective oculomotor system and are directly related to the adaptability of the opposite system. Accordingly, high CA/C ratio is associated with poor vergence adaptation and robust accommodative adaptation and a similar relation for AC/A ratio where the ratio is inversely related to the adaptability of accommodation and directly related to the vergence adaptation (Schor, 1988). Similar results were demonstrated in another study (Schor & Horner., 1989) where convergence insufficiency subjects exhibited low AC/A ratio, robust accommodative

adaptation, high CA/C ratio, and poor vergence adaptation. Convergence excess subjects exhibited high AC/A ratio, poor accommodation, low CA/C ratio, and robust vergence adaptation. It is also apparent from our previous study discussed in section 2 that vergence adaptation reduces the CA response. This evidence suggests that the CA cross-link is driven by only the fast fusional vergence and not by the combined output of fast and slow components supporting Schor's model. If such is the case, then vergence adaptation occurring during positive fusional amplitude testing must reduce the CA output thereby decreasing the target blur. This forms as the basis from which the current study was developed to test how vergence adaptation pattern influences CA response before and after training.

Literature evidence suggests that the slow fusional vergence mechanism is amenable to training to restore normalcy resulting in alleviation of near visual symptoms (Cooper et al., 1983). Evaluation of the ability of the oculomotor system to adapt to prism induced heterophoria before and after orthoptic treatment in a group of convergence insufficiency subjects showed improvement in the subjects' ability to adapt to prism associated with ameliorated symptoms (North & Henson., 1982 & 1992). This change in the ability of the vergence system to adapt robustly following fusional vergence training modifies certain oculomotor parameters that are measured clinically.

The goal of positive fusional vergence training is to see an overall improvement in the convergence which is reflected in parameters like near point of convergence (NPC), distance and near exophoria, positive fusional convergence, etc that define an individual's convergence

ability. Amplitude of convergence defined by NPC has been shown to improve with training (North and Henson., 1992; Brautaset and Jennings., 2006; Daum, 1986; Cohen, 1984; Cushman & Burri., 1941; Adler, 2002; Birnbaum, 1999). Although some studies reported no change in the near exophoria (Brautaset & Jennings.,2006; Dalziel, 1981; Cushman & Burri; 1941), other studies have indicated that the near exophoria decreases (Daum, 1986; Manas, 1958; Flom, 1959; Cohen, 1984; Mann, 1940). However, distance heterophoria (reflecting tonic vergence) has been shown not to change following orthoptic training at distance & near distances (Cushman & Burri., 1941; Brautaset & Jennings., 2006).

The effects of positive and negative vergence training on the visual system have been studied by Daum (1982) in which a variety of visual training procedures were administered on asymptomatic young adults with normal binocular vision. Positive vergence amplitude at both distance and near increased after a week of training itself but negative vergence both at distance and near did not change significantly with visual training. The results of the above study are similar to that of Vaegan's (1979) except that the magnitude of improvement in vergence ability reported by Vaegan appears to be considerably smaller in BO values. A study on the effect of positive fusional vergence training on fusional vergence ability and asthenopia in patients with convergence insufficiency (CI) showed that upon completion of training all patients had reduced asthenopic symptoms with an increase in the BO fusional range (Cooper et al 1983). Also several other studies have reported an increase in the positive fusional vergence range following training (North and Henson., 1992; Dalziel, 1981; Brautaset & Jennings., 2006).

Past evidence suggests that the cross-link ratios can be altered with orthoptic training. AC/A ratio was found to increase with positive fusional vergence training (Manas, 1958; Flom, 1959). In contrast to the above findings, Brautaset and Jennings (2006) found no significant difference in the AC/A ratio and near exophoria before and after training despite showing a faster decay of the accommodative after-effect following vision therapy in clinical cases of CI. Vergence adaptation was found to have no effect on stimulus AC/A ratio (Rosenfield et al., 2000) and as well as on response AC/A ratio (Rainey, 2000) supporting Ebenholtz & Fisher (1982) model in which the cross-links originate after the adaptation element in the feed forward loop. Modifiability of CA/C ratio with orthoptics was reported by Hung and his co workers (1986) in a group of symptomatic subjects. According to Schor's model, an improved ability of the slow component to adapt will cause a concomitant reduction in the fast component response thereby reducing the crosslink gain. Brautaset and Jennings (2006) evaluated the effect of orthoptic treatment on stimulus CA/C ratio in a group of CI subjects. Their results show that there is no significant change in the crosslink ratio after the training despite an improvement in the vergence adaptation ability. This is in contrary to the present theory of Schor's model.

It is apparent from the above studies that clinically measured BO to blur & break values improve with training. The basic mechanism that is acting to change the positive fusional vergence amplitude needs attention. It is known that vergence adaptability improves with training. Increased positive fusional amplitude could be due to a reduction in the CA/C ratio caused by the improved vergence adaptation or it could be due to rapid prism adaptation reducing the CA during BO amplitude testing. The static values of the cross-link ratios have been shown not to

change significantly with positive fusional vergence training (Brautaset & Jennings, 2006). There could be a possibility that the improved vergence adaptability following training is not reflected in the static value of the cross-link ratio and is manifested in the cross-link response that is measured dynamically over time. It is important to distinguish the vergence adapted state from vergence adaptation trained state. Following training, measures are taken under vergence adaptation trained state which is different from measuring parameters under vergence adapted state. It has been previously reported that prism viewing increase the AC/A ratio both in human (Judge & Miles., 1985; Miles et al., 1987) and in monkeys (Morley et al., 1988, 2002). In order to have a clear understanding, it is important to evaluate the cross-link ratios under vergence adaptation and compare it with that of the responses obtained following vergence training that alters the pattern of vergence adaptation. We hypothesize that the increased BO to blur value following vergence training results from the increased speed of prism adaptation and CA reduction and that the static values of the cross-link ratios remain the same after the training. This is because, we postulate that vergence training alters only the slow fusional vergence mechanism and does not change the neural cross-link gain. In this paper, cross-link ratios and base-out to blur value have been evaluated before positive fusional vergence training, under induced vergence adapted state and after the training. Also the decay rates of phoria and CA response have been monitored over time before and after training. The improved vergence adaptability following training has been explained using simulations of Schor's model by arbitrarily modifying the gain and time constant of slow fusional vergence component to demonstrate rapid and greater magnitude of adaptation and CA response reduction following training. The Simulation results are discussed in appendix IV.

## **4.3 Methods**

### **4.3.1 Study Participants**

Eleven healthy emmetropes between the ages of 19 and 30 years (Mean  $24.63 \pm 2.8$  years) were recruited from the student / staff population at the School of Optometry at the University of Waterloo. The study was approved and received full ethics clearance from the Office of Research Ethics, University of Waterloo. Participants with 6/6 visual acuity who met Morgan's criteria (1944) for distance and near heterophoria (using modified Thorington method), distance and near positive and negative fusional amplitudes, Near Point of Accommodation (NPA) (monocular and binocular), Negative Relative Accommodation (NRA) and Positive Relative Accommodation (PRA) and with normal near point of convergence (Scheiman & Wick., 2002, page no.9) were enrolled in the study.

### **4.3.2 Instrumentation**

Accommodative responses were measured using the commercial Power Refractor (MultiChannel Systems, Reutlingen, Germany) after individual calibration was carried out. Refer to appendix B for calibration results. The method of measurement was similar to study 1 discussed in chapter 3. All the accommodative responses were measured when fusion was reported by the participants. Although the binocular accommodative response was measured for 5 seconds, only measures from right eye were averaged for analysis purpose. Heterophoria measures were taken using the modified Thorington technique (MTT) (Borish, 1975). The magnitude of the phoria was quantified using a custom made tangent scale whose validity and repeatability was evaluated at

0.4m (Results are summarized in appendix C). Phoria measurement was similar to study 1 procedure discussed in chapter 3.

### **4.3.3 Experimental Procedure**

Following the screening visit, if the participants met the eligibility criteria, the following baseline measures (before positive fusional vergence training) were recorded on the same day of the screening visit.

#### **Pre-Training Measures**

##### **Stimulus AC/A ratio (sAC/A)**

The sAC/A ratio was measured using the gradient method where ophthalmic lenses ranging from +2.00D to -2.00D in 1D steps were introduced in front of the eyes and the corresponding near phoria was recorded using MTT. The slope of the linear fit plotted with induced lenses (in D) along x axis and the resultant phoria (in  $\Delta$ D) along y axis was considered as the sAC/A ratio.

##### **Stimulus CA/C ratio (sCA/C)**

Accommodation feedback loop was opened by asking the participants to fixate at a DoG placed at 0.4m. BO prisms of magnitude 0, 3, 6, 9, & 12 were introduced in front of the left eye and the concomitant change in the accommodative response upon subject reporting fusion was measured from the right eye using the fast screening mode in the power refractor. The sCA/C ratio was calculated from the slope of the linear fit plotted using the convergence stimulus (in MA) along x axis and the resultant accommodative response (in D) along y axis.



## **Measurement of Phoria and Convergence Accommodation during 15 Minutes of Prism Adaptation**

This experiment was conducted under open-looped accommodation where participants binocularly fixated at a DoG at 0.4m through 12  $\Delta$  BO in front of the left eye for 15 minutes. The target was displayed from a laptop to a miniature 1.77" LCD monitor placed at a distance of 0.4m from the subject and was projected on to a semisilvered mirror placed in front of the subject as shown in figure 4.1.



**Figure 4.1 showing DoG target projected onto the semisilvered mirror from the LCD monitor at 0.4m**

Phoria and CA response immediately following the prism insertion were recorded. Phoria and accommodative measures were monitored at the end of every 3 minute (@ 3, 6, 9, 12 & 15 minutes) of binocular viewing through the prism for 15 minutes. Adaptation of the induced

heterophoria towards the baseline and the reduction of convergence accommodation response over time were fit using an exponential decay function using Graphpad Prism (GraphPad software Inc, USA). The exponential functions obtained before and after training were compared using the Graphpad Prism software.

### **Measurement of BO to Blur, sAC/A & sCA/C ratios under induced Vergence Adapted state**

This test was basically done to evaluate the induced vergence adaptation effect on the measured oculomotor parameters with adapting stimulus in place under closed-loop accommodation and was compared with the values that were obtained before and after the positive fusional vergence training. This procedure shows the output of the specific parameters when the adapting stimulus is active. This experiment was done on a separate session (with at least 24 hours of interval from the screening visit) in order to avoid the influence of vergence adaptation that had taken place during the baseline measures discussed earlier in the section and was done before the training sessions. Participants fixated on the cartoon picture (shown in figure 4.2) of high contrast (>85%) and luminance of  $31.5 \text{ cd/m}^2$  displayed on a miniature LCD monitor and was projected on to a semisilvered mirror. Considering the boredom factor, this high contrast color target was chosen over a high contrast text.



**Figure 4.2 showing a high contrast fixation target used for vergence adaptation under dual closed-loop condition**

A Baseline phoria measure was obtained.  $12 \Delta$  BO was introduced in front of the left eye and the phoria immediately following prism insertion was recorded. Participants were asked to binocularly fixate on the high contrast target with the prism in place for 15 minutes. Upon completion of 15 minutes of the near task, the following measurements were taken with the adapting stimulus in place: near BO range, sAC/A ratio and sCA/C ratio. Ratios were measured with the same procedure described earlier in the section and vergence amplitude was measured using prism bar. Finally, phoria measure was taken to ensure that the vergence adaptation had taken place.

#### **4.3.4 Positive Fusional Vergence Training**

Participants underwent training for 2 weeks, with a total of 6 sessions, (3 sessions per week). Each session lasted for 25 to 30 minutes and each participant had a total of approximately 180 minutes of training. During each session, positive fusional vergence was trained conventionally (Scheiman & Wick., 2002) using variable tranaglyphs and aperture rule. The basic principle behind the training was to keep the accommodative demand constant at 0.4m and increase the convergence demand by increasing the distance between the accommodation and the vergence planes. This was accomplished by increasing the distance between the targets seen by the right and the left eyes. At the end of each training session, participants' positive fusional vergence amplitude was recorded using a synaptophore. Slides with second (flat fusion) and third (stereopsis) degree fusion targets with suppression checks were used. Crossed disparity was increased gradually and the BO to blur, break and recovery values were recorded.

#### **Variable Tranaglyphs**

The equipment consists of red and green slides that differ from each other by color and disparity. The subject wears red and green goggles in front of the right and left eyes respectively. To increase the convergence demand, the red slide is moved towards right and the green slide is moved towards left. The right eye views the target on left side and the left eye sees the target on right side. The scale at the bottom of the tranaglyphs indicates the amount of prismatic demand at a given target separation at 0.4m viewing distance.

The working principle of tranaglyphs was clearly explained to the participants. The participants wore the red / green goggles. The slides were aligned to zero prismatic demand at 0.4m to start

with. The convergence demand was slowly increased in increments of  $2\Delta$  while they maintained single fused and focused target. During each session, the demand was increased until a maximum point where participants could fuse and focus the letters on the target. The procedure was repeated for 10-15 minutes with 1 or 2 minutes break in between and the highest magnitude of the prism the participants could fuse and focus was noted at the end of each session.

### **Aperture Rule**

Aperture rule is based on the principle of chiasmatic fusion (Scheiman & Wick., 2002), where the visual axes are crossed relative to the fixation distance of the targets at 0.4m. Aperture rule is a ruler like apparatus, consisting of 12 fixation cards of varying disparities, ranging from  $2.5\Delta$  to  $30\Delta$ . The cards contain flat-fusion (second degree) and stereopsis (third degree) targets and as well as suppression controls. Each card contains targets seen by the right and left eyes separately. For convergence therapy, a single aperture plastic slide is used to change the plane of convergence, while the plane of accommodation is held constant at the plane of the cards. Once the participants were familiar with the aperture rule working principle, the cards were placed at the zero point marked on the ruler. The convergence demand was increased by placing the single aperture slide at different positions on the scale that corresponds to the card number. Participants were asked to report once they achieve single and clear and the times at which fusion and focusing took place were noted using stop clock. During each session, the maximum number of slides the participants could fuse and focus was noted. Participants were asked to fixate at a distant object and sufficient breaks were given between two vergence demands. Home exercises were not administered and hence compliance with training was controlled by the investigator.

#### **4.3.5 Post Training Measurements**

The post training measurements were made in the week immediately following the two weeks of training. This was done to make sure that the post training measurements were made when the effect of the learned behaviour of the slow fusional vergence mechanism to adapt robustly as a result of training was still effective. The following measurements were recorded: NPC, Distance and near heterophoria, Distance and near positive and negative fusional amplitudes, lag of accommodation, NRA & PRA, sAC/A & sCA/C ratios and Phoria and CA response during 15 minutes of prism adaptation under open-looped accommodation.

#### **4.4 Data Analysis**

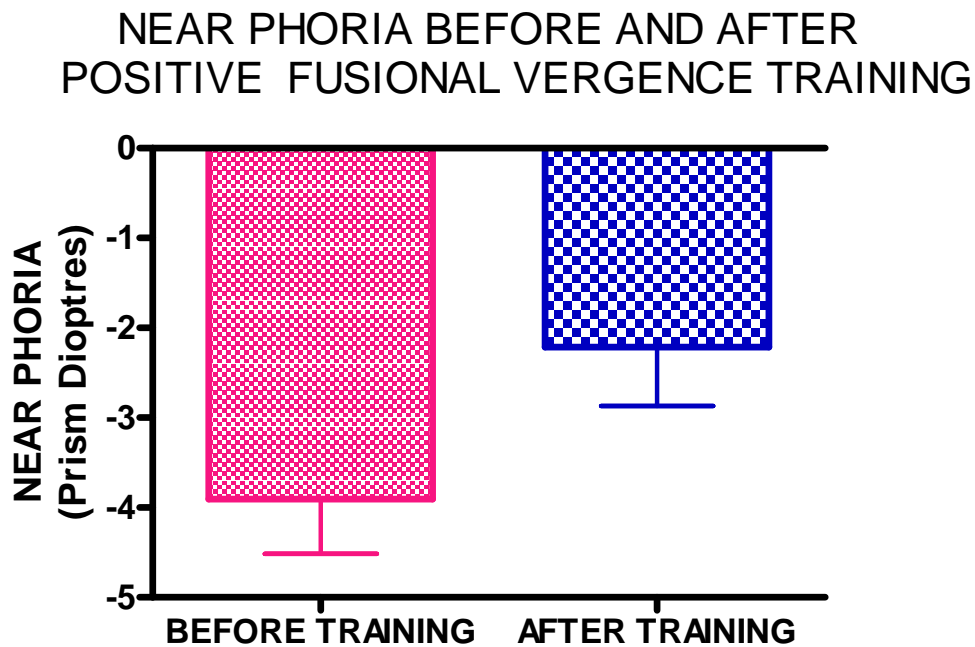
NPC, distance and near phoria, PRA & NRA, negative fusional amplitudes at distance and near, lag of accommodation and positive fusional amplitude at distance were analyzed using a paired 't' test before and after training. Phoria and CA responses measured over time for 15 minutes under open-loop accommodation were fitted with exponential decay function with GraphPad Prism software. The reduction of the induced exophoria and CA were plotted as function of time and exponential functions were fit to determine the rates and magnitudes of phoria adaptation and CA response reduction. The exponential decay functions before and after training were compared by the software used to look for robustness in the vergence adaptation and reduction of CA response following positive fusional vergence training. The software gives the rate constant and the time constant (time taken for 63% of total adaptation and CA response reduction) is defined as the inverse of the rate constant. Rate constant, plateau (where the response saturates) and the amount of phoria adaptation and CA response reduction of the function before and after

training were compared. AC/A ratio, CA/C ratio and BO to blur value at 0.4m taken during baseline, under vergence adapted state and following training were analyzed using repeated measures ANOVA. Since 25 to 30% of the participants had difficulty in fusing all the 12 slides in the aperture rule during the first 2 sessions of week 1, fusing and focusing time could not be analyzed completely. Hence, fusing and focusing times for slide 6 in the aperture rule whose convergence demand is  $15\Delta$  at 0.4m (with IPD = 6cm) were averaged for week 1 and week 2 and were analyzed with paired 't' test. This was just done to evaluate the trend in the fusing and focusing times with training. BO to blur values measured with synaptophore at the end of each training session were averaged for week 1 and week 2 and were analyzed with paired 't' test.

#### 4.5 Results

The near point of convergence was shown to improve significantly ( $t = 6.127$ ,  $p = 0.000$ ). Distance heterophoria was not significantly different following vergence training ( $t = 1.312$ ,  $p = 0.219$ ). The mean change in the magnitude was less than 1  $\Delta$ D.

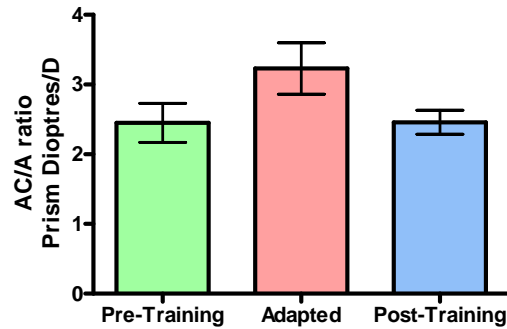
However, post training, near heterophoria was found to be significantly different ( $t = 4.132$ ,  $p = 0.002$ ) from the pre training value showing less exophoria following training. The mean amount of exophoria reduction was 1.4 $\Delta$ . This is shown in figure 4.3.



**Figure 4.3 showing a significant eso-shift in the near phoria following training (Error bars indicate  $\pm$  1 SE).**

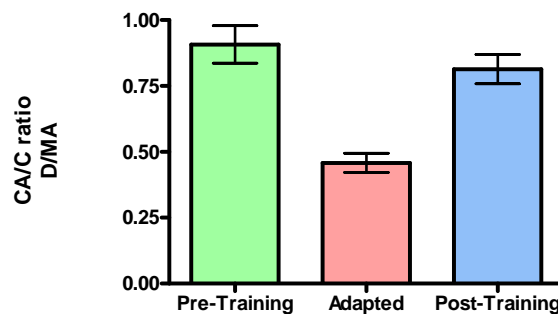


There was no significant difference between pre and post training AC/A ratios ( $p = 0.999$ ). However, the AC/A ratio measured under the vergence adapted state was found to be small but significantly increased from the pre training ( $p = 0.023$ ) and post training ( $p = 0.025$ ) values as inferred from figure 4.4.



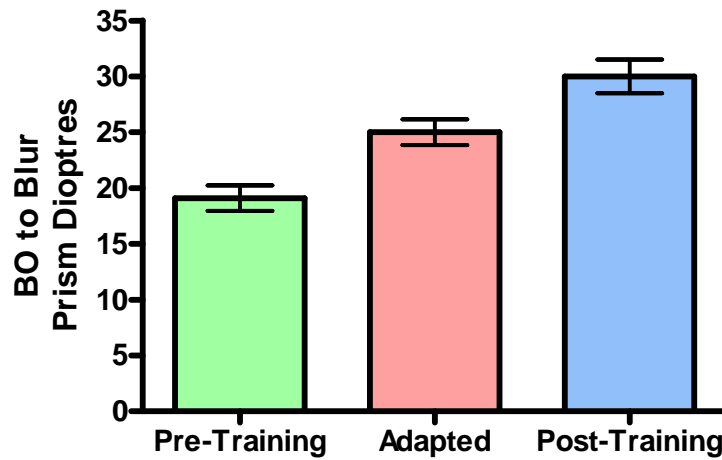
**Figure 4.4 showing no significant difference in the AC/A ratio before and after training with a significant increase in the ratio under vergence adapted state induced with 12Δ BO (Error bars indicate ± 1 SE).**

Similar results were found for CA/C ratio. CA/C ratio did not change significantly following training ( $p = 0.146$ ). However, the CA/C ratio that was measured under vergence adapted state was found to be significantly reduced from the pre training ( $p = 0.000$ ) and post training ( $p = 0.000$ ) values, seen from figure 4.5.



**Figure 4.5 showing no significant difference in the CA/C ratio before and after training with a significant decrease in the ratio under vergence adapted state induced with 12Δ BO (Error bars indicate ± 1 SE).**

BO to blur value was found to be significantly increased from the pre training measure both under vergence adapted state ( $p = 0.000$ ) and following training ( $p = 0.000$ ). Also, post training value was significantly different from the value that was obtained under vergence adapted state ( $p = 0.001$ ). This is illustrated in figure 4.6.



**Figure 4.6 showing significant increase in the BO to blur value both under vergence adapted state and following training (Error bars indicate  $\pm 1$  SE).**

Exponential fit of phoria adaptation and CA response monitored once every 3 minutes for a 15 minute duration under open-loop accommodation before and after training showed that the phoria adapted faster with greater magnitude following training. Rate constant, plateau and magnitude of adaptation of the exponential function were significantly different following training ( $p = 0.000$ ) indicating faster and greater amount of adaptation. (Refer to figure 4.7).

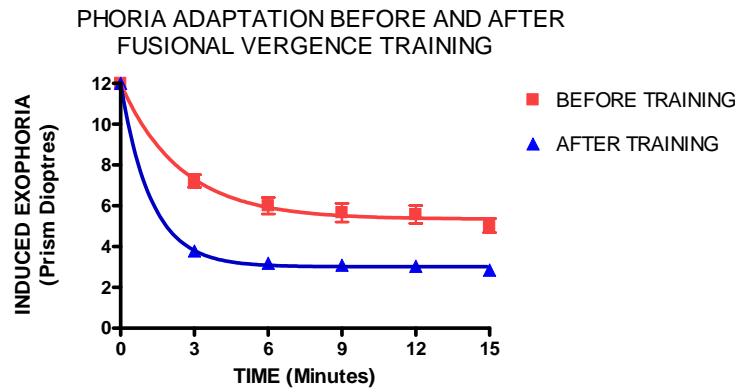


Figure 4.7 showing greater and faster phoria adaptation following training (Error bars indicate  $\pm 1$  SE).

Exponential function before training was found to be,

$$\text{Equation 1, } Y = 6.638 * e^{-0.4073X} + 5.347$$

Where rate constant = -0.4073, plateau = 5.347 and amount adapted = 6.638 $\Delta$ . The time constant can be found as the inverse of the rate constant ( $1/0.4073 = 2.45$  minutes).

After training, the exponential function fitting the results was,

$$\text{Equation 2, } Y = 8.986 * e^{-0.8086X} + 3.014$$

where rate constant = -0.8086, plateau = 3.014 & amount adapted = 8.986 $\Delta$ . The time constant was 1.24 minutes.

Similarly, for CA, there was a significant difference in the rate constant ( $p = 0.014$ ), plateau ( $p = 0.002$ ) and the amount of reduction ( $p = 0.016$ ) of the exponential functions before and after training indicating faster and greater amount of CA response reduction following training, as shown in figure 4.8.

Exponential function before training was found to be,

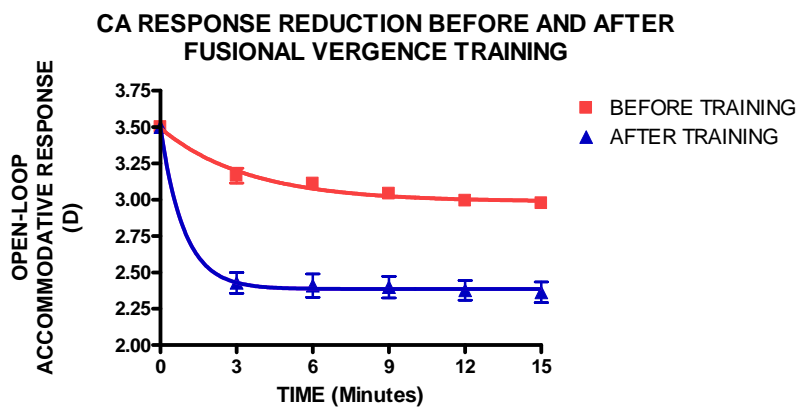
**Equation 3,  $Y = 0.5062 * e^{-0.2883X} + 2.987$**

where rate constant = -0.2883, plateau = 2.987 & reduced CA amount = 0.5062D. The time constant was 3.46 minutes.

The exponential function after training was,

**Equation 4,  $Y = 1.114 * e^{-1.077X} + 2.386$**

where rate constant = -1.077, plateau = 2.386 & reduced CA amount = 1.077D. The time constant was 0.98 minutes.



**Figure 4.8 showing increased rate and magnitude of reduction in CA response following training (Error bars indicate  $\pm 1$  SE).**

Robust and greater magnitude of BO prism adaptation and CA response reduction as a result of positive fusional vergence training were simulated using Schor's model (1992) and the simulation results are discussed in appendix D. Simulations were run by altering the slow component gain and the time constant since empirical results showed rapid decay of induced heterophoria and CA response and greater magnitude of adaptation and reduction in the CA response following training. Gain value and time constant were chosen arbitrarily to demonstrate the trend in the vergence adaptation reducing the CA response rapidly following training. This is because of the fact that the gain values and the time constants specified in Schor's model usually get multiplied by or divided by other gains or transfer functions to arrive at the required output. The output of the fast and the slow integrators can be thought of as the amplitude and rate of neuronal spiking that get converted into units of diopters and meter-angles after passing through the biomechanical plant.

## Training Results

The average fusing time for week 1 and week 2 were not significantly different ( $t = 2.093$ ,  $p = 0.090$ ). However, the average focusing time for week 1 and week 2 were significantly different ( $t = 2.432$ ,  $p = 0.035$ ) from each other.

Average Focussing Time During Week 1 & Week 2 Of Training Using Aperture Rule

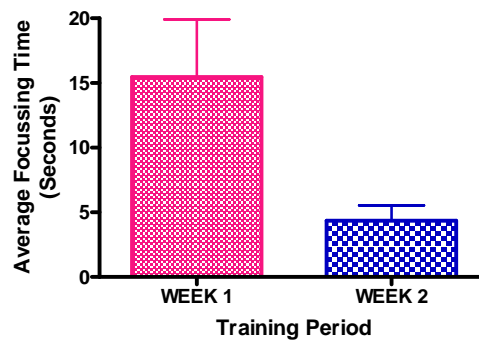


Figure 4.9 showing faster target focusing during week 2 of training, significantly different from week 1 of training (Error bars indicate  $\pm 1$  SE).

Also the average BO to blur value measured at week 1 was significantly different ( $t = 3.789$ ,  $p = 0.0035$ ) from the average value measured during the second week of training.

Average BO to blur value during week 1 & week 2 of training

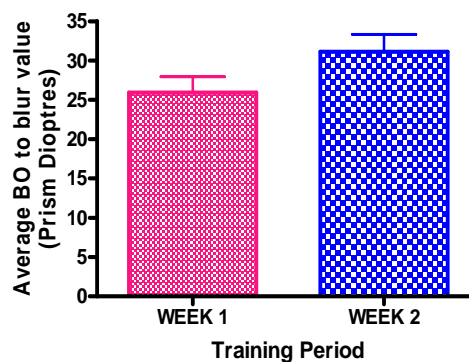


Figure 4.10 showing significant increase in the BO to blur value during week 2 of training (Error bars indicate  $\pm 1$  SE).

There was no significant difference in the lag of accommodation, NRA & PRA, negative fusional amplitudes at distance and near and positive fusional amplitude at distance ( $p = >0.05$ ) before and after positive fusional vergence training. Although BO to blur value at distance showed an increased trend, there was no significant difference between pre and post training. BO to break value could not be analyzed before and after training since for the majority of the participants following the training, the value lay beyond the testing range of the prism bar.

## **4.6 Discussion**

The objective of the positive fusional vergence training is to increase the positive fusional vergence amplitude (Scheiman & Wick, 2002) and to increase the speed of the fusional vergence response. A significant improvement in the NPC following training reflects an overall improvement in the amplitude of convergence as expected. The most common approach in the positive fusional vergence training is to maintain the accommodative demand at the plane of regard at 0.4m, while the convergence demand is altered by moving the plane of vergence towards the subject. The greater the separation between the plane of accommodation and the plane of vergence is, the greater the demand on the fusional vergence system is. To maintain a sharp focus at 0.4m, stable accommodation has to be maintained and to maintain binocular single vision without experiencing diplopia, one must converge to the required amount when BO prisms are added. The oculomotor system does this by using the positive fusional vergence. Also, since accommodation is held constant, accommodative convergence cannot aid the convergence response, thus increasing the demand on the fusional vergence system. However, increases in vergence accommodation would need to be responded to by accommodation and accommodative divergence works against the fusional convergence. With training, the slow fusional vergence mechanism, receiving input from the forced fast fusional vergence, learns to adapt faster, thus reducing the load on the fast fusional component, allowing it to respond to the subsequent change in the vergence stimulus. Therefore, the reduced fast component gives less input to the CA cross-link which reduces the target blur while adding BO prisms.



#### **4.6.1 Adaptability of vergence and CA response with training**

Vergence adaptability in the BO direction at near improved significantly with positive fusional vergence training. This is evident from the pre and post training exponential decay functions of phoria adaptation and CA response reduction. Phoria adaptation occurred faster with a significant increase in the rate constant of the decay function of the induced exophoria following training. The magnitude of phoria adaptation increased significantly following training. Similar results were found for the CA response. The slow fusional component was adapting faster (as evident from the rate of phoria adaptation) and reduced the fast fusional component which in turn reduced the CA response faster (as reflected from the increased rate constant post training). Also an increased amount of CA reduction following training was found. This was also shown in before and after training simulation outputs (discussed in appendix D).

#### **4.6.2 Cross-link ratios under vergence adapted state and following training**

The reduction in the CA response with vergence adaptation was not reflected in the post training static CA/C ratio showing no significant difference between pre and post training CA/C ratios. However this result is expected by considering the methods used to determine is the CA/C ratio. The convergence accommodation (CA) value is measured from the open-loop accommodative response which is taken immediately following prism insertion. At this point the fast fusional component drives the CA cross-link. This method does not allow slow fusional component to act and thereby reduce CA and thus would have resulted in the same ratio as obtained before the training. It would appear that the vergence training did not alter the neural cross-link gain, but modified only the rate and degree of vergence adaptation.

The finding that the CA/C ratio was significantly reduced from the pre and post training values would be predicted since under vergence adaptation convergence accommodation (CA) output would be reduced. This does not preclude vergence adaptation causing a reduced neural cross-link gain for CA/C; however it would not be necessary if the fast system was being reduced quickly. The results of the current study are consistent with that of the findings by Brautaset & Jennings (2006) who showed no change in the cross-link ratios with training in CIs. Similarly, in this study there was no significant increase in the sAC/A ratio following training whereas the sAC/A ratio measured under vergence adapted state was small but significantly increased from the pre and post training values. This could be justified by the following explanation. Phasic component of blur-driven accommodation drives the AC cross-link (Jiang, 1996) and this neural cross-link gain is not altered by training slow fusional vergence component. However, under the vergence adapted state, due to reduction in CA cross-link gain, there is a possibility that the AC cross-link gain is altered at the neural level resulting in an increased AC/A ratio under vergence adapted state. The results are consistent with earlier findings in which the AC cross-link gain was found to increase by a small ( $\approx 0.3 \Delta D$ ) but significant amount, with phoria adaptation in humans (Miles et al., 1987; Judge & Miles., 1985) and also in monkeys (Morley et al., 1992). In the current investigation, stimulus AC/A ratio was measured and not the response ratio. The increase in the AC/A ratio under the vergence adapted state could be due to a reduction in the accommodative response. Since accommodative response was not measured, this is unclear. However, accommodative response was found to remain unchanged with vergence adaptation in monkeys while AC was increased (Morley et al., 1992).

#### **4.6.3 BO to blur with training**

Blur that occurs during BO fusional amplitude testing is because of increased CA with fusional effort. Following training, with increase in the BO prisms and with increase in the speed of prism adaptation, the reduction in the fast component and hence the reduction in CA, results in the enhanced BO to blur value. Under vergence adapted state, the reduced CA cross-link gain is reflected in the increased BO to blur value.

#### **4.6.4 Fusing & Focusing ability with training**

With training, the speed with which fusion takes place was not significantly different between week 1 and week 2 of training. However, target focusing time was significantly reduced during the second week of training indicating faster focusing. This could be explained by the following: when an individual is given a target to fuse under dual closed-loop conditions, the fast fusional mechanism acts immediately to fuse to avoid diplopia. This fast component driving the CA cross-link results in the target blur. With sustained viewing, when the slow fusional component starts acting, the reduced fast vergence output reduces the CA and this clears the target to be in focus. Thus with training, since the slow component output acts faster to reduce the CA, the subject could focus the target faster during week 2 than during week 1 of training. The results add as supporting evidence to Schor's view on the vergence adaptation reducing the CA cross-link.

#### **4.6.5 Phoria changes with training**

Near phoria responses were less exophoric or more convergent in position following training. Results demonstrated no change in the AC/A ratio. Hence the change should be either due to a change in tonic vergence innervation or tonic combined with proximal vergence. Literature evidence suggests no change in the tonic vergence innervation with vergence adaptation (Rosenfield & Gilmartin., 1988). Assuming the distance perceived gain to be constant before and after training, the proximal vergence output should be constant before and after training. There could be a possibility that training might have caused orthophorization causing a decrease in the exophoria reflected by the slowly decaying slow vergence component output while measuring the heterophoria.

Other parameters such as lag of accommodation, NRA & PRA, NFV at distance and near, PFV at distance and NPA did not change significantly following training showing no effect of positive fusional vergence training on these parameters.

## 4.7 Conclusions

Positive fusional vergence training increases the rate of onset and amplitude of vergence adaptation which is apparent from the dynamic CA measured overtime demonstrating faster and as well as greater magnitude of CA response reduction following training. Although positive fusional vergence training results in robust vergence adaptation and thereby produces faster CA response reduction, the absolute value of the neural cross-link gain remains unaltered after the training and hence shows no change in the post training static measure of the CA/C ratio. Similarly, AC cross-link gain remains unchanged with training which is obvious from similar AC/A ratio before and after training. However, the ratios are modified when measured under vergence adapted state presumably due to reduced neural gain. Hence the improved vergence adaptability in BO direction reducing the CA response cannot be identified in the static measures of cross-link gains and can be seen only in measures taken dynamically overtime. Clinically, enhanced BO to blur value following training is a resultant of improved vergence adaptability during addition of BO prisms resulting in faster reduction of CA response. Although vergence adaptation changes the cross-link ratios which is apparent from the ratios measured under vergence adapted state, this change will not get manifested in the ratios measured under vergence adaptation trained state since only static values are measured. Hence, the cross-links should be measured dynamically over time to see the actual effect of training on these ratios.

## Chapter 5 General Discussions and Conclusions

Empirical measures from the studies discussed in this thesis have clarified the role of vergence adaptation on reducing the output of convergence accommodation. Vergence adaptation resulting in the reduction of the CA response over time supports Schor's model in which the cross-link components originate between the fast and the slow components and the reduction in the output of the fast component results in the reduction of the output of the cross-link component. However, the study results do not support the view of cross-links initiating adaptation. Individuals who can exert normal adaptation of vergence and accommodation experience comfortable vision during sustained viewing. It is known that during BO fusional amplitude testing, with increase in the prism strength, the increase in convergence results in an increase in the CA response and this leads to the target blur which is compensated by the negative accommodation to a limit. In normal individuals, with increase in BO prisms, the simultaneous increase in the output of the slow fusional vergence component reducing the fast component output, results in the reduction of CA response and this reduces the target blur resulting in normal BO to blur value. Studies have shown that individuals experiencing near vision symptoms possess deficient vergence adaptation mechanism. In the symptomatic individuals, due to deficient prism adaptation, with forced fusional convergence and thereby an increased CA, target blur occurs sooner. Universally, positive fusional vergence training has been shown to improve symptoms with an increase in the amplitude of convergence which is apparent from the enhanced BO fusional amplitude. From Schor's model, one can predict that that enhancement of the BO fusional range could be due to the change in the CA/C ratio, precisely a decrease in the CA/C ratio and a concomitant increase in the AC/A ratio. A recent study on the effect of

vergence training in convergence insufficiency patients showed constancy of the cross-link ratios following training though an improvement in the vergence adaptability was demonstrated (Brautaset & Jennings, 2006). It is important to distinguish between vergence adapted state and vergence adaptation trained state. In this thesis, cross-link ratios measured under vergence adapted state have been shown to modify significantly, whereas cross-link ratios measured under vergence adaptation trained state (following training) show no significant change. Since vergence training alters only the speed with which vergence adapts and does not alter the actual neural cross-link gain, ratios are not expected to change following training. It is only during sustained viewing, the cross-link magnitudes are changed with adaptation which is apparent from the study results. The improved vergence adaptability is reflected only in the cross-link response measured dynamically over time showing faster and greater magnitude of adaptation and thereby faster and greater magnitude of CA response reduction. However, this learned behavior of rapid adaptation is manifested in the BO to blur value tested clinically. As discussed earlier, with increase in BO prisms, and with increase in the adaptation, the reduced CA output gives rise to enhanced BO to blur value following positive fusional vergence training.

In conclusion, the positive fusional vergence training prescribed to convergence insufficiency patients improves only their vergence adaptability by increasing the speed of prism adaptation reducing the CA response over time. The absolute values of the cross-link ratios are not expected to change with training and only when the cross-link responses are measured over time, the modification caused by adaptation gets manifested. Further investigations are required to study the underlying mechanisms in other accommodative and vergence dysfunctions. Also

investigations are needed to evaluate the changes in the dynamics of accommodation, vergence and their interactions with training.



## Appendix A

### GENERATION AND VALIDATION OF NEAR doG TARGET

Target was generated using the equation given by Wilson (1978),

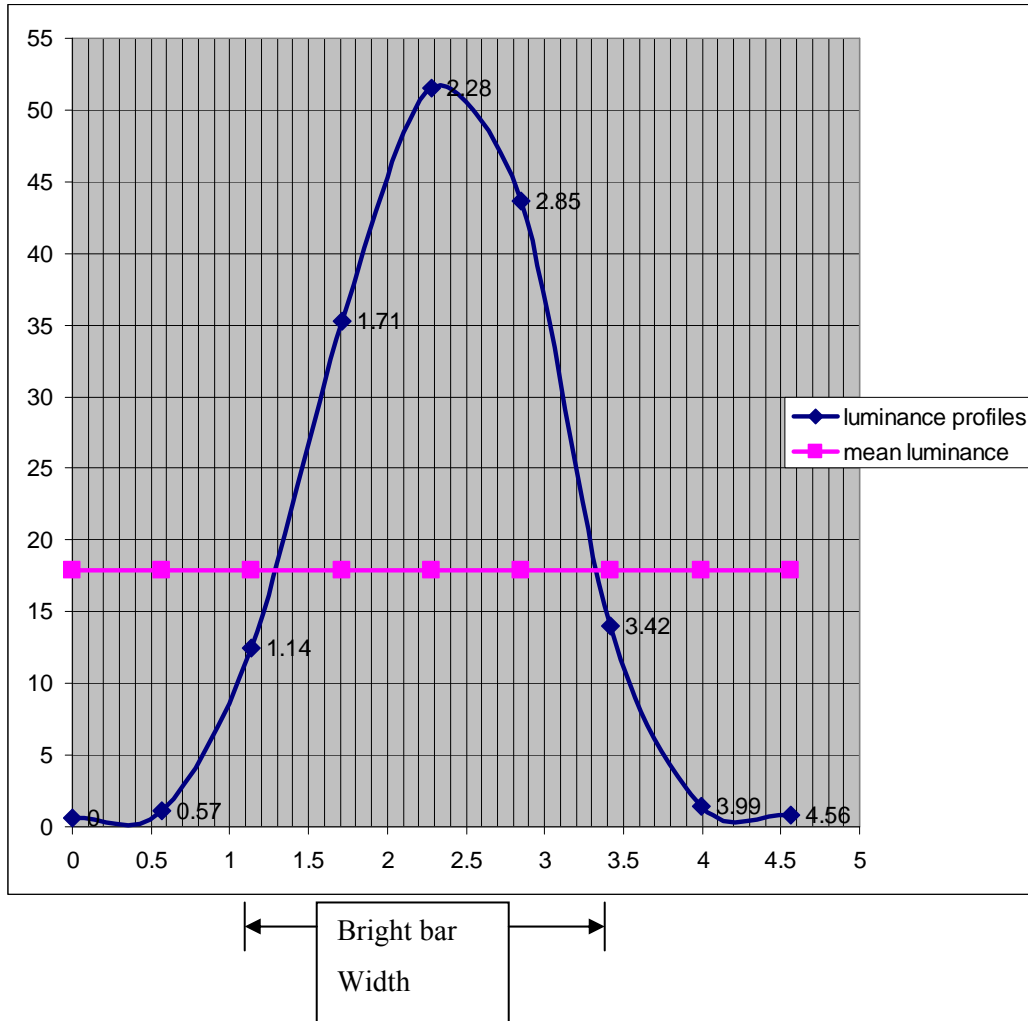
**Equation 5**,  $\text{DoG}(x) = 3 \exp(-x^2/\sigma^2) - 2\exp(x^2/2.25\sigma^2) + k$

where,  $k$  is the mean luminance,  $\sigma$  is the space constant, the ratio of space constant of the broad Gaussian to that of the narrow one is 1.5:1.0.

The target was generated using the following MATLAB program code:

```
Function z = plotTarget (sig, k)
% Height of the target
Hght = 200;
% range of the input array
x = -2*sig: 0.05:2*sig;
%Gaussian function
y = 3*exp(-(x/sig).^2)) - 2*exp(-(x.^2/(2.25*sig.^2))) + k;
% repeat to generate the matrix
for i = 1:Hght, z(i,:) = y;
End
% compute the maximum and minimum values for plot
maxVal = max(max(z));
minVal = min(min(z));
% display the plot
imshow(z,[minVal,maxVal]);
```

The luminance profile of the doG target (shown in figure) was measured using photometer and the spatial frequency was calculated using,  $SF = 1/ 2.28$  (b), where b is the bright bar width in degrees.



**Figure 5.1 showing the luminance profile across the DoG target**

The spatial frequency of the target was calculated to be 0.212c/deg, subtending 2.068 degrees at 0.4m.

The effectiveness of the generated near doG target in opening the accommodation feedback loop was tested by comparing the accommodative responses obtained using doG, pin-hole and under monocular closed-loop accommodation condition. Five adults whose mean age was 24.8 years with mean refractive error of -0.25DS volunteered as subjects. At 0.4m, accommodative responses (AR) to the lenses ranging from 0 to -3.00D were recorded from the right eye using the fast screening mode in the power refractor under the following three conditions:

- 1) Monocular closed-loop accommodation, where subjects fixated at a high-contrast target and the relative changes in the AR with the insertion of negative lenses were recorded.
- 2) With pin-hole (0.5mm), subjects fixated at a high-contrast target placed through an infra-red pinhole in the right eye and the corresponding changes in the AR with the insertion of negative lenses were measured.
- 3) With 0.2 c/deg DoG target, subjects fixated at the central bright bar of the doG, negative lenses were placed and the corresponding changes in the AR were measured.

Accommodative responses obtained under the three above conditions were compared using 2-way ANOVA. Results showed that there was a significant difference in the accommodative responses measured between the conditions 1 and 2 and between the conditions 1 and 3 ( $p < 0.01$ ). But there was no significant difference between the conditions 2 and 3 ( $p > 0.05$ ). It can be seen from figure that there was no change in the accommodative response with an increase in negative lens power which confirms that the subjects were not accommodating with negative lenses while viewing the doG target and as well as with pin-hole. The mean slope for the doG target was 0.09 and for the pin-hole was -0.06. From the above results, it was clear that the generated near doG

target with 0.2 c/deg of spatial frequency was effective enough in not stimulating the reflex accommodation (results similar to findings with pin-hole).

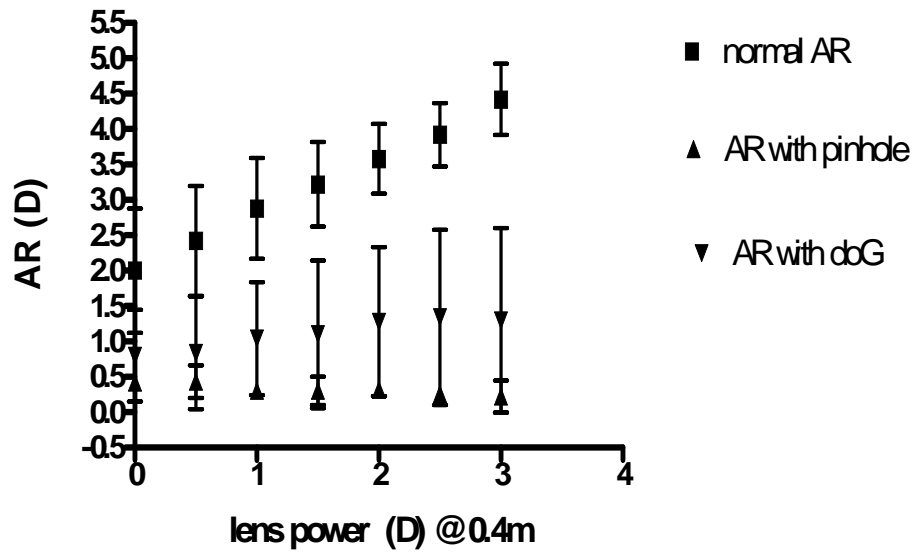


Figure 5.2 showing accommodative responses measured under normal, through pin-hole and with DoG target with the change in the accommodative stimulus using negative lenses at 0.4m (Error bars indicate  $\pm 1$  SE)

## **Appendix B**

### **CALIBRATION OF POWER REFRACTOR**

It was necessary to calibrate the power refractor before it could be used to take the convergence accommodation measures. It was necessary to check whether the inbuilt reference calibration equation of the instrument is appropriate for the individuals participating in this study because Schaeffel et al (1993) reported that the individual variations in the fundal reflectance characteristics might influence the light distribution in the pupil and thereby could result in variability among individuals. Accordingly, a calibration procedure was carried out.

The subjects were asked to fixate at a high contrast target placed at 6m distance with their left eye. An IR filter (Kodak 87B, IR filter, Rochester, NY) was placed in front of the right eye which blocked visible light, but allowed IR light from the photorefractor. Ophthalmic lenses (in 1D step from +4 to -2D) were introduced in front of right eye. The induced refractive error in the right eye was measured using fast screening mode in power refractor. The induced refractive error (along x axis) and the measured refractive error (along y axis) were plotted and fitted with a linear regression. The slope of the fit was compared against 1:1 relationship.

Figure 5.3 shows a plot of induced refractive error (X) versus measured refractive error (Y) for 11 subjects. The pooled slope, across all subjects, was 1.1 ( $r^2 = 0.96$ ) which was not significantly different from the 1:1 relationship. The calibration study showed that there was a linear change in the measured refractive error (using power refractor) with increasing induced refractive error within the range (+2.00 to -4.00 D) tested. Hence the calibration could be used to measure

convergence accommodation measures which are usually within the above range in the current investigation.

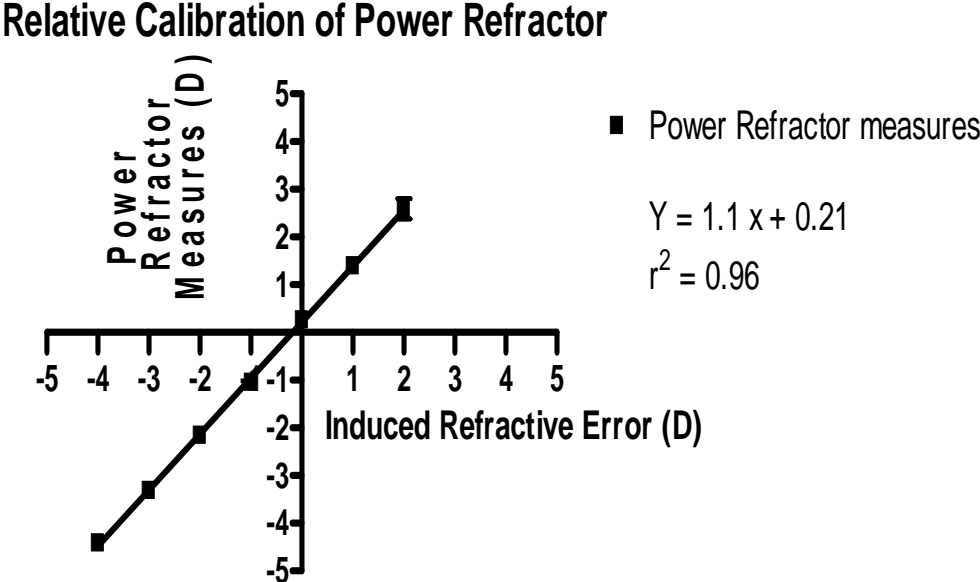


Figure 5.3 showing calibration plot with a slope of 1.1

## **Appendix C**

### **VALIDITY AND REPEATABILITY OF THE MODIFIED THORINGTON SCALE**

Past evidence suggests that the phoria measures taken using MTT have been shown to have good repeatability and validity (Rainey et al., 1998; Escalante & Rosenfield., 2006; Sreenivasan, 2007). The accuracy of the custom designed MTT was assessed in 11 emmetropic adults by comparing the MTT measures with an objective prism neutralized alternate cover test. The prism neutralized cover test was performed while participants fixated at a high contrast target (6/12 Snellen equivalent) at 0.4m. An occluder was alternately moved between the eyes and the as the phoria measure.

The repeatability of MTT measure was assessed by repeating the measures on two different occasions of testing using MTT. The Bland and Altman (1986) technique was used to determine the 95% limits of agreement ( $\text{Mean}_{(\text{diff})} \pm 1.96 * \text{SD}_{(\text{diff})}$ ) for comparing the two methods of testing and for the repeatability of the MTT measure.

Statistical analysis using paired 't' test showed no significant difference ( $p > 0.05$ ) between the mean near phoria measures obtained using prism neutralized cover test and MTT, although CT showed an exophoric bias of  $0.35 \Delta$ . The Bland & Altman technique was used to determine 95% limits of agreement ( $\text{Mean}_{(\text{diff})} \pm 1.96 * \text{SD}_{(\text{diff})}$ ) for comparison of phoria measures between the two methods and also for the repeatability of phoria measures using MTT. Figure 5.4 shows good agreement between CT and MTT with 95% limits of agreement ranging between  $\pm 1.17$

$\Delta D$ . This suggests that the phoria obtained using MTT would 1.17  $\Delta D$  higher or lower than the objective measures obtained using prism neutralized CT.

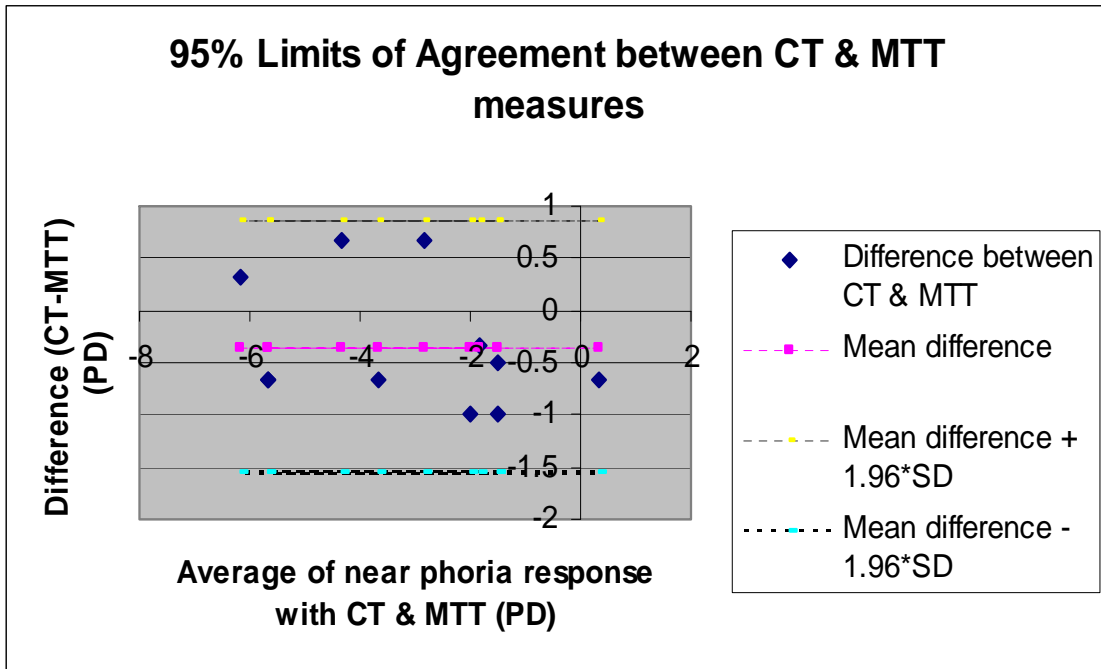


Figure 5.4 shows the comparison between phoria measures obtained using prism neutralized CT and MTT



The coefficient of repeatability (COR) of MTT was found to  $\pm 1.80 \Delta D$ , and hence a change greater than  $1.80 \Delta D$  will be considered clinically significant. The repeatability of near phoria using MTT is shown in figure 5.5.

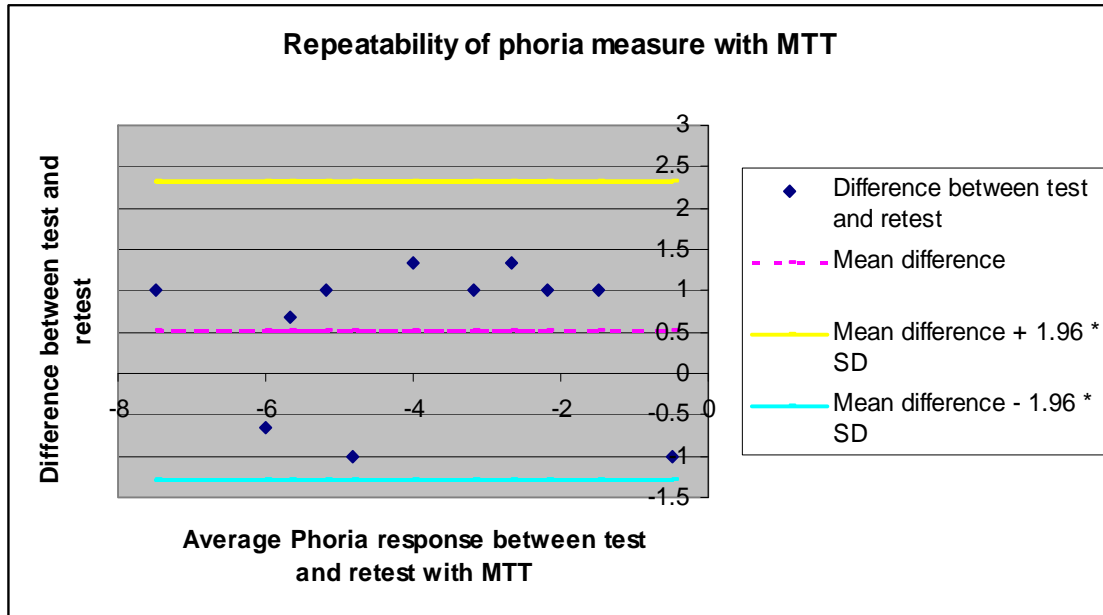


Figure 5.5 shows average and mean differences between test and retest phoria measures using MTT to calculate the repeatability (COR  $\pm 1.80 \Delta D$ )

## Appendix D

### SIMULATION RESULTS

#### Study 1 Experiment (a) Effect of vergence adaptation on CA response

The experiment results were verified using Schor's dual interactive model (Schor, 1992) in which the cross-links are placed between the fast (phasic) component and the slow (tonic) component and the cross-links receive input from the fast components.

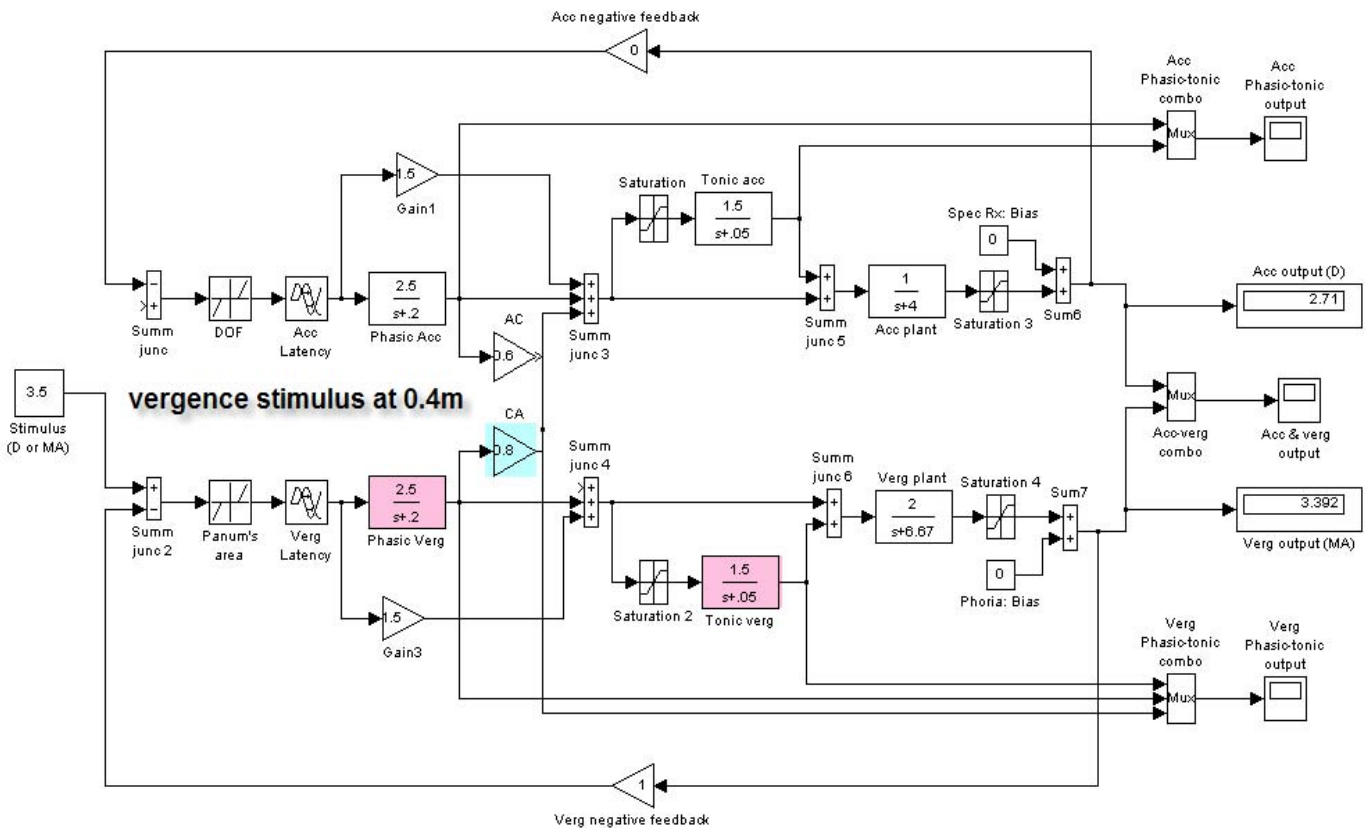
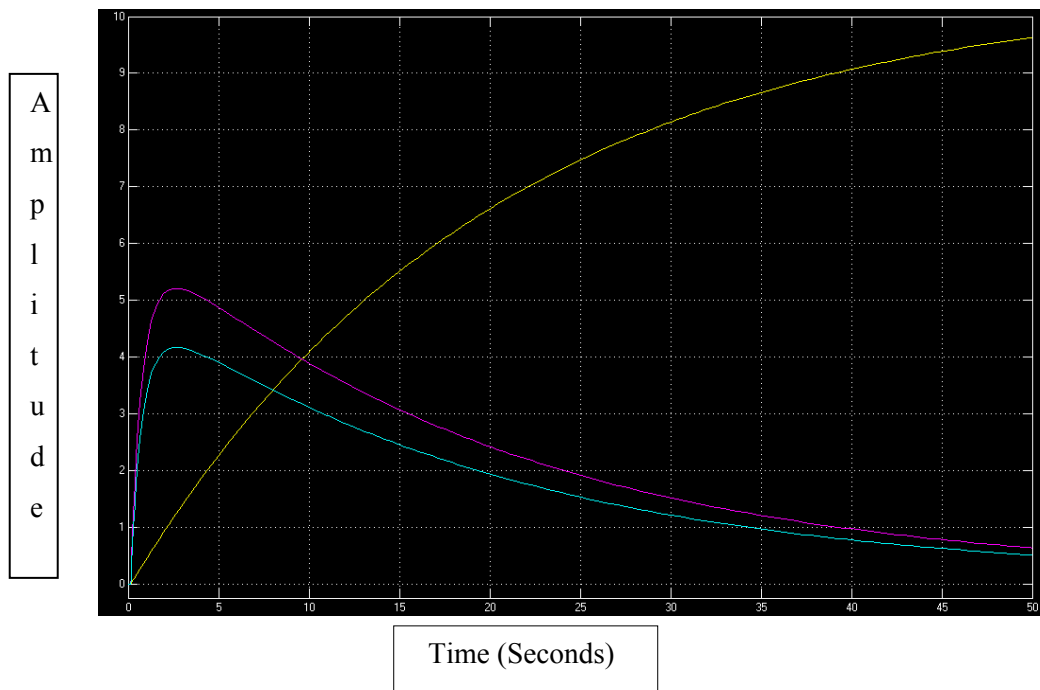
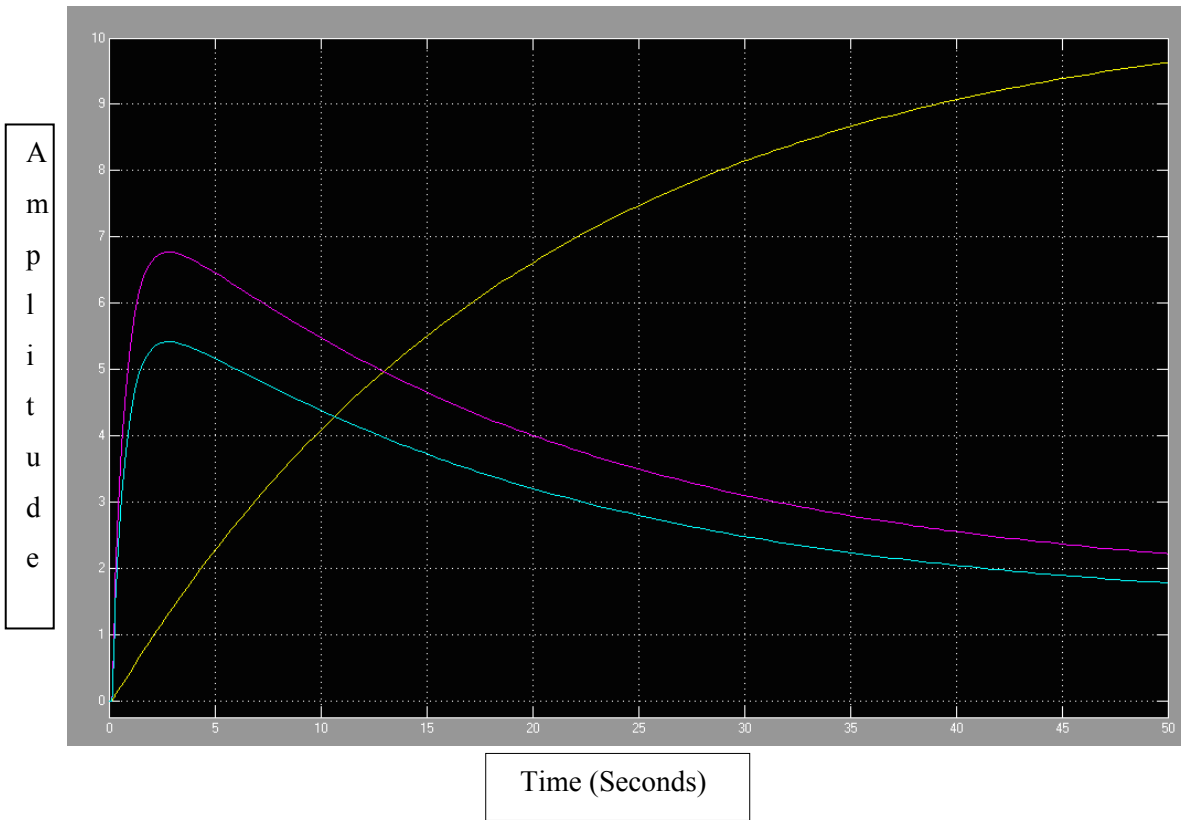


Figure 5.6 showing Schor's model used for running simulations. CA cross-link is placed between the phasic (fast) and the tonic (slow) vergence components and feeds into junction 3 in the accommodation system. Accommodation feedback loop was opened by altering the feedback gain as zero. Vergence stimulus was placed at 0.4m. Model adapted from Schor 1992.

Simulations were run using MATLAB Simulink under open-looped accommodation for 6 and 12  $\Delta D$  vergence stimuli. Simulation results shown in figures 5.7 & 5.8 demonstrate a decrease in the CA response along with a decrease in the fast fusional vergence component with the onset of slow fusional vergence output (vergence adaptation). Gain and time parameters used were as specified in figure 5.6.

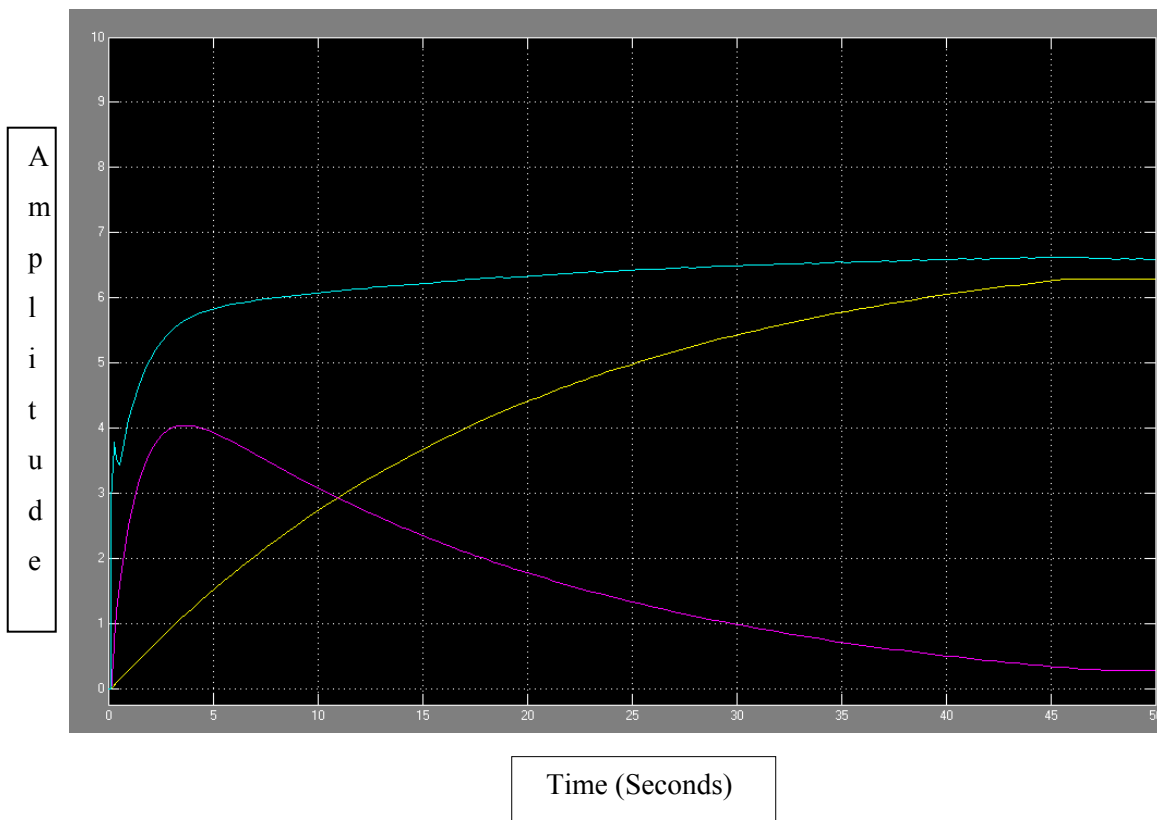


**Figure 5.7 showing MATLAB Simulink output showing decrease in the CA response with vergence adaptation using  $6\Delta$  BO stimulus. X axis shows time in seconds and y axis gives the amplitude of the responses. Yellow line refers to slow fusional vergence response, purple refers to fast fusional vergence response and blue line refers to the CA response.**



**Figure 5.8 showing MATLAB Simulink output showing decrease in the CA response with vergence adaptation using  $12\Delta$  BO stimulus. Yellow line refers to slow fusional vergence response, purple refers to fast fusional vergence response and blue line refers to the CA response.**

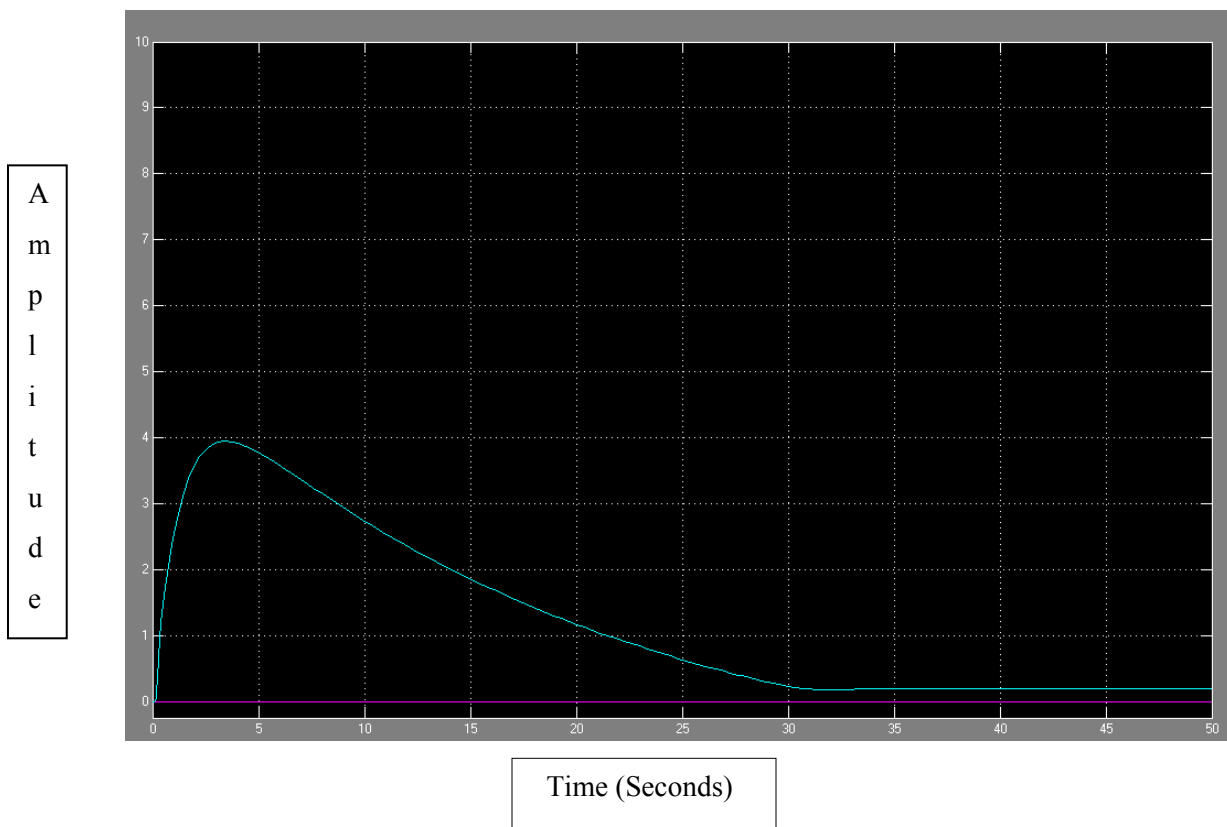
However, when the CA cross-link was placed after the slow fusional vergence, simulation results showed no reduction in the CA response with vergence adaptation under open-looped accommodation. This is consistent with Fisher and Ebenholtz model in which the cross-links receive input from both the fast and the slow components. Gain and time parameters used were as specified in figure 5.6. This is depicted in figure 5.9.



**Figure 5.9 illustrating MATLAB Simulink output showing no reduction in the CA response with decrease in the fast fusional output with vergence adaptation using 6 BO stimulus. Simulations were run with CA cross-link placed after the slow fusional vergence component. Yellow line refers to slow fusional vergence response, purple refers to fast fusional vergence response and blue line refers to the CA response.**

### Study 1 Experiment (b) CA stimulation on accommodative adaptation

According to Schor's model, cross-links feed into the tonic element of the opposite system inducing an adaptation in the accommodation system. The result of the current study shows no accommodative adaptation when CA was stimulated with  $12\Delta$  BO at 3.5m. This gives the possibility of the cross-links feeding into the summing junction of the opposite system. When Schor's model was modified by feeding the CA cross-link into the summing junction 5 instead of junction 3 in figure 5.6 in the accommodation system, simulation results showed absent accommodative adaptation with CA stimulation. Gain and time parameters used were as specified in figure 5.6. This is depicted in the MATLAB Simulink output shown in figure 5.10.

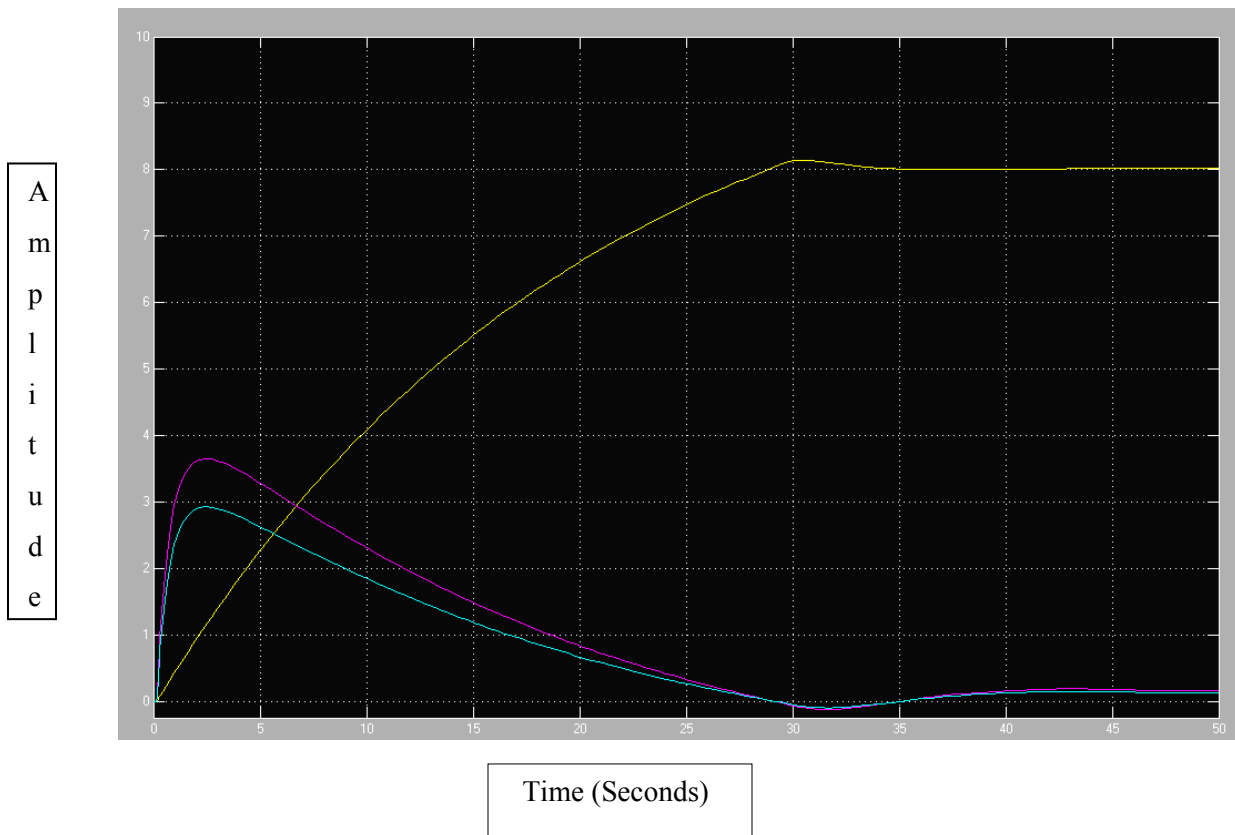


**Figure 5.10 showing MATLAB Simulink output showing no accommodative adaptation with stimulation of CA using  $12\Delta$  BO stimulus. Purple line (flat) refers to the accommodative adaptation and blue line refers to the CA response.**

## Study 2 Effect of positive fusional vergence training on vergence adaptation

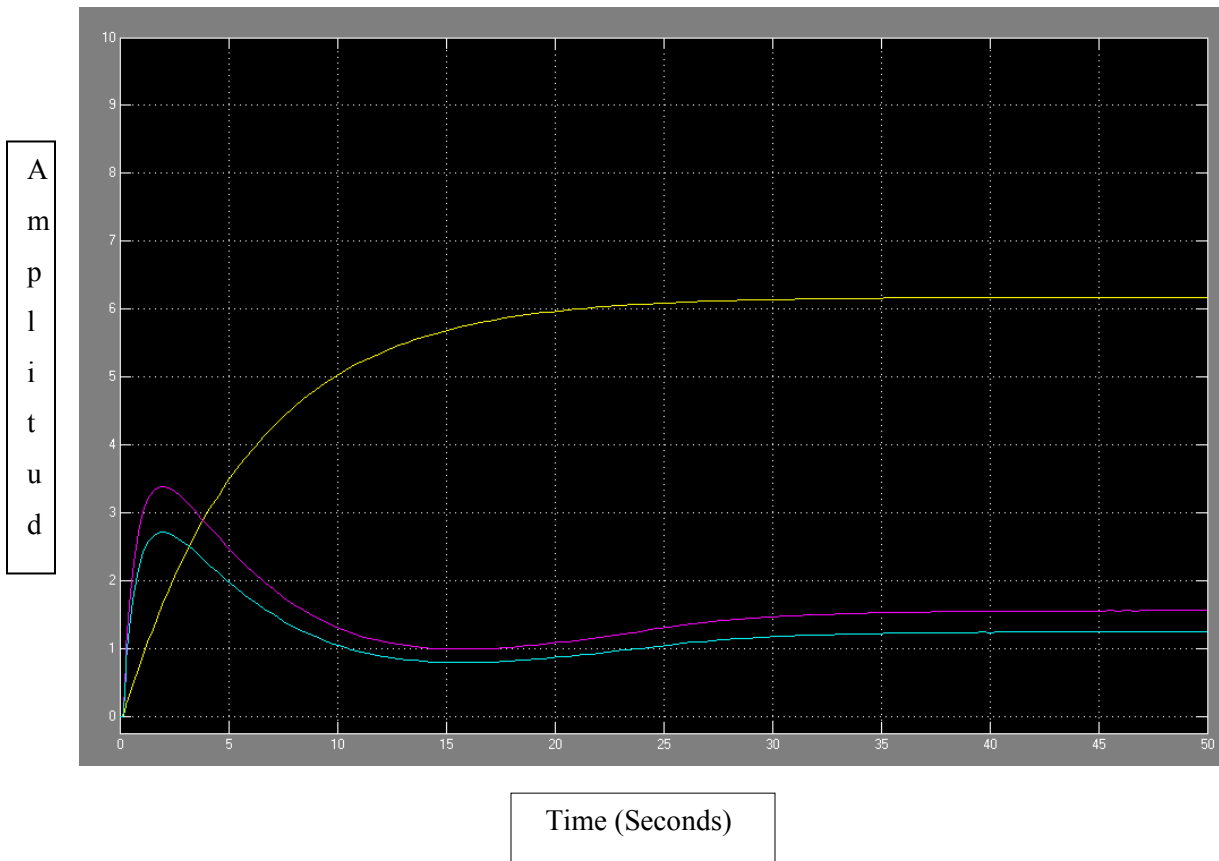
The study results discussed in chapter 4 suggest that both the gain of tonic vergence and its time parameters are altered by training such that its rate of onset is increased as is its amplitude. As such modeling such a change would be suggestive of changes in both the time constant and gain of the slow component (tonic vergence in the model figure 5.6).

The patterns of vergence adaptation and CA response reduction before training were simulated using gain and time constant specified in Schor's model. This is shown in figure 5.11.



**Figure 5.11 shows reduction in the CA response with vergence adaptation before training for 2.5MA of vergence stimulus with the slow component gain of 1.5 and time constant of 0.05. Yellow line refers to the slow fusional vergence response, purple line refers to the fast fusional vergence response and the blue line refers to the CA response**

The pattern of vergence adaptation and CA response reduction after training were simulated by increasing the gain and time constant of the tonic vergence arbitrarily while the phasic vergence parameters were unaltered. The values were chosen to demonstrate increased magnitude and the speed of vergence adaptation reducing the CA response concomitantly. This is shown in figure 5.12.



**Figure 5.12 shows rapid reduction in the CA response with vergence adaptation after training for 2.5MA of vergence stimulus with the slow component gain of 2.25 and time constant of 0.15. Yellow line refers to the slow fusional vergence response, purple line refers to the fast fusional vergence response and the blue line refers to the CA response**



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