Adaptation to near addition lenses – Effect of AV/A ratio and age

By

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Abstract

AIM: The primary purpose of this thesis was to evaluate the pattern of changes to accommodation and phoria when pre-presbyopic individuals perform near work for 20 minutes with +2D lenses. In addition, the thesis also investigates the effect of the accommodative vergence cross-link (AV/A) and age on binocular adaptation to addition lenses.

METHODS: Accommodation was measured using the PowerRefractor (Multichannel Systems, Germany) and phoria was measured using the modified Thorington Technique. Twenty four pre-presbyopic and emmetropic individuals (11 adults and 13 children) participated in the study. All participants fixated a near target at a distance of 33 cm for 20 minutes with +2D (lens condition) and without (no lens condition) +2D addition lenses. Binocular and monocular changes in accommodation and near phoria were measured at the outset and at 3, 6, 9, 15 and 20 minute intervals.

RESULTS: ***Effect of +2D lenses on accommodation and phoria:*** The emmetropic adult participants exhibited lag of accommodation under the no lens condition (binocular: 0.51 ± 0.12D; monocular: 0.64 ± 0.15D) that were eliminated (under monocular viewing) and reversed (exceeded demand by 0.51 ± 0.11 D under binocular viewing condition) with the addition of +2D lenses. The near phoria showed a significant increase towards exophoria by 6 ± 0.56 ΔD upon introduction of +2D lenses. Sustained near viewing with +2 D lenses resulted in significant reduction of the binocular focus alone (not monocular focus) after 3 minutes of binocular viewing (magnitude of reduction: 0.24D; $P<0.01$). The exophoria also showed a concomitant reduction after 3 minutes of fixation at the near task (Magnitude of reduction: 3.6 ± 0.6 ΔD; $P<0.001$). The magnitude and rate of vergence adaptation, determined using an exponential function, was found to be 4.6 ± 0.21 ΔD and 2.12 minutes respectively for the emmetropic adult participants.

Effect of age on vergence adaptation: A pattern of significant reduction in phoria and binocular focus similar to the adult participants was observed in young children. Analysis of the vergence adaptation curves in the two age groups did not show any significant difference in both the magnitude as well as the rate of phoria adaptation within the age range tested (Magnitude of adaptation - Adults: 4.65 ΔD; Children: 4.51 ΔD; $P > 0.05$; Time constants -Adults: 2.12 minutes: Children: 1.53 minutes, $P > 0.05$).

Effect of AV/A ratio on vergence adaptation: The stimulus (St-AV/A) and the response AV/A (R-AV/A) ratios were determined and the participants were divided into two groups (low and high AV/A ratio) under both the conditions. The result indicated that, under both testing conditions (stimulus and response AV/A), the individuals with higher AV/A ratios demonstrated greater magnitudes of vergence adaptation than those individuals with lower ratios (Magnitude of adaptation: Low St-AV/A = 4.12 ΔD; Low R-AV/A= 4.25ΔD; High St-AV/A = 4.88 ΔD; High R-AV/A = 4.65ΔD; $P<0.05$)

CONCLUSIONS: Introduction of near addition lenses initiated an increase in exophoria and convergence driven accommodation. Vergence adaptation occurred after 3 minutes of binocular viewing thus reducing exophoria and convergence driven accommodation. The magnitude and completeness of phoria adaptation were seen to depend on an individuals AV/A ratio with greater magnitude and incomplete adaptation observed in participants with higher AV/A ratios. Age, within the limits of the study did not appear to influence phoria adaptation with near addition lenses.

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Dedication

This work is graciously dedicated to the almighty for showering his blessings

And

To my parents, sister and brother for providing me immense love, support and encouragement without which this work would not have been possible

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1 LITERATURE REVIEW

Near addition lenses are primarily prescribed to older adults to compensate for presbyopia, the loss of accommodative ability with age (Borish, 1975). However, plus lenses are also prescribed to pre-presbyopic individuals for a variety of conditions. The most common reasons for application of plus lenses in these individuals include: treatment of convergence excess (Scheiman & Wick., 1994b), alleviating near point visual stress (Birnbaum, 1985; Birnbaum, 1993; Gruning, 1985) or for attenuation of myopia progression (Greenspan, 1981; Gwiazda et al., 2003; Leung & Brown., 1999; Oakley & Young., 1975). Since near addition lenses are prescribed in order to modify the accommodative and/ or vergence system the following section will provide a brief review of the components of accommodation, vergence and their interactions.

1.1 Basics of accommodation, vergence and their interactions

When fixation is changed from far to near, three related motor acts take place: the eyes converge to reduce binocular disparity, the crystalline lens power increases to focus on the near target and the pupils constrict. These three responses have been termed the "near-response" or the "near triad" (Fincham & Walton., 1957; Morgan, 1968)

1.1.1 Accommodation - Definition and mechanism

In humans, accommodation refers to the process by which changes to the dioptric power of the crystalline lens produce a clear and focused image on the retina (Fincham, 1951). The accommodative process involves the accommodative plant which consists of the ciliary muscle, the crystalline lens and zonules. When vision is directed to a distant object, the fibers of the ciliary muscle relax causing increased tension on the zonules which flattens the lens and holds it in its conoid un-accommodated state. When viewing a near object, the ciliary muscle contracts and releases the tension on the zonular fibers allowing the elastic forces of the crystalline lens to mold it into a spherical shape with increased thickness and convexity. Along with these changes, the anterior and posterior radius of curvature increase (anterior greater than posterior) resulting in an increase in the refractive power of the crystalline lens (Helmholtz theory of accommodation cited in (Borish, 1975)).

The primary stimulus for accommodation is the blurred retinal image (Heath, 1956). The afferent pathways that stimulate accommodation commence with the stimulation of the retinal receptors by the defocused retinal image. The blur signals pass through the visual pathway (optic nerve- chiasm-optic tract- lateral geniculate body) and are transmitted to cortical area 17 and to the parieto-temporal areas for further processing. The neural signal is then transformed into a motor command at the midbrain - Edinger-Westphal nucleus. The efferent pathway involves transmission of motor command via the oculomotor nerve, the ciliary ganglion and the short ciliary nerves. However, anatomical evidence for the synapse in ciliary ganglion is controversial with some studies showing no synapse (Westheimer & Blair., 1973) and others showing evidence for synapse in the ciliary ganglion (Ruskell & Griffiths., 1979). The efferent pathway ends at the ciliary muscle wherein a change in the state of contraction alters the refractive power of the crystalline lens and thus attains an in-focus image on the retina.

The accommodation system receives mutually-antagonistic, dual innervation from the autonomic nervous system. It is composed primarily of a parasympathetic component but also receives innervation from the sympathetic system (Gilmartin et al., 1992). The parasympathetic system is mediated by the muscaranic receptors, whose stimulation results in increased accommodation and is characterized by a rapid temporal response that is completed in 1-2 sec (Campbell & Westhiemer., 1960). In comparison, the sympathetic system is characterized to be primarily inhibitory, provides relatively small response magnitude (less than 2D) and exhibits a delayed temporal response (10-40 sec) (Gilmartin et al., 1984; Gilmartin & Hogan., 1985; Gilmartin, 1986).

1.1.2 Vergence - Definition and mechanism

Vergence refers to the process of providing single binocular vision by movement of the two eyes in opposite direction thereby bringing the images of the bi-fixated target onto the corresponding retinal points (Westhiemer & Mitchell., 1956; Westheimer & Mitchell., 1969). Convergence occurs in response to a crossed retinal disparity (objects located in front of the horopter) and refers to the movement of the eyes towards midline. On the other hand, divergence refers to the movement of the eyes away from the midline and occurs in response to uncrossed disparities (object located behind the horopter).

In humans, eye movements are executed by three pairs of extraocular muscles in each orbit: a pair of horizontal rectus muscles (medial and lateral rectus), a pair of vertical rectus muscles (superior and inferior rectus) and a pair of oblique muscles (superior and inferior oblique). The medial, superior and inferior rectus muscles and the inferior oblique are innervated by the oculomotor nerve. The lateral rectus muscle is innervated by the abducens nerve and the superior oblique is innervated by the trochlear nerve.

The sensory stimulus for vergence is the disparity between the relative locations of the images on each retina (Stark et al., 1980). This disparity is detected by the visual cortex neurons which presumably project the signal to the vergence center in the midbrain. The precise "vergence" center for humans is not known however, evidence from primates indicate that their location is likely in the midbrain, closer to the oculomotor nucleus (Judge & Cumming., 1986; Mays, 1984; Mays et al., 1986). Three types of neural cells, the vergence burst neurons, vergence tonic neurons and vergence burst-tonic neurons have been identified to play an important role in overall vergence control (Mays, 1984; Mays et al., 1986). The vergence burst-neurons (pulse-like neurons) fire just before and during the actual vergence response and act as an input to the vergence neural integrator. The output of the neural integrator, the step, is carried by the vergence tonic neurons which fire just before the vergence movement with the firing rate proportional to the vergence angle (Mays, 1984). The vergence burst-tonic neurons probably reflect the combined burst and tonic neuronal signals and may be the "near-response cells" that input directly to the oculomotor neurons. They have been identified to contain the pulse and step neural controller with functions for generating and maintaining the eye position respectively (Mays et al., 1986).

1.1.3 Units of measurement of accommodation and vergence

Accommodation is measured in diopters (D), which are defined as the reciprocal of the linear value of the viewing distance. The stimulus to accommodation (AS) is the theoretical amount of accommodation required at a particular distance while accommodative response (AR) refers to the actual amount of accommodation exerted by the eye at that target distance. The difference between the stimulus and response accommodation is called the accommodative error. Focusing errors that result from insufficient accommodation (AR<AS) are termed lag of accommodation and place the

conjugate focus behind the retina. In contrast, errors that result from excessive accommodation (AR>AS) are termed lead of accommodation and place the conjugate focus in front of the retina.

1.1.3.1 Accommodative stimulus-response curve

The relationship between stimulus of accommodation and its response is often represented by the stimulus–response curve (Morgan, 1944; Morgan, 1968). This can be generated by altering optical vergence of the target either by varying target distance in physical space, varying target position (for e.g. within a badal optical system) or with spherical lenses placed in front of the eyes. Figure 1 shows a typical stimulus- response curve with the dashed line indicating a perfect (1:1) relationship between the stimulus and the response.

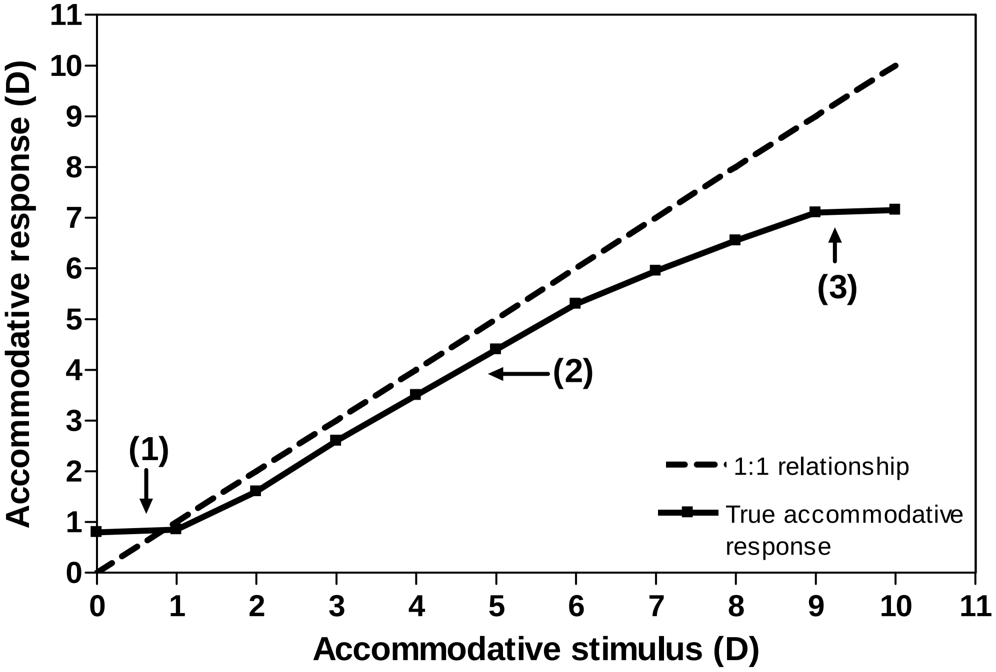


Figure 1: Accommodative Stimulus-response curve (adapted from Ciuffreda & Kenyon., 1983)

Empirical measures (solid line) typically show a pattern which can be divided into three different zones (Ciuffreda & Kenyon., 1983). Zone (1) represents the region exhibiting a lead in accommodation for lower stimulus levels. This response reflects the bias induced by the tonicity of the ciliary muscle and is almost constant (Ciuffreda & Kenyon., 1983). Zone (2) indicates a lag of accommodation for intermediate stimulus levels with progressively increasing lags for higher stimulus demands. The slope of the stimulus-response curve at the intermediate stimulus levels is less than unity in young adults (Millodot & McBrien., 1986). With further increase in the stimulus to accommodation, the accommodative response saturates (Zone 3) indicating that the maximum amplitude of accommodation has been reached.

Vergence can be expressed in two units: Meter angle (MA) and prism diopters (ΔD). A meter angle is numerically the reciprocal of the fixation distance in meters and analogous to the diopter. For example, a target at 33 cm would require 3MA of convergence just as it would require 3D of accommodation. The prism diopter on the other hand considers the individuals interpupillary distance in addition to the fixation distance. It is calculated by multiplying MA of convergence with the pupillary distance of the individual. For example, the stimulus to convergence for an adult with an interocular separation of 6 cm viewing a target at 33cm would be 18 ΔD. The prism diopter is conventionally used when prism powers are defined.

1.1.3.2 Definition of heterophoria and its types

Proper alignment of the eyes is brought about by a normally functioning sensory and motor fusion mechanism. If sensory fusion is artificially suspended (for example by occluding one eye) a measurable relative deviation of the visual axes may be observed.

The deviation disappears and the visual axes return to the proper relative positions upon regaining sensory fusion. This latent deviation is termed heterophoria. The dictionary of visual science (Hofstetter & Griffin., 2000) defines heterophoria as “the tendency of the lines of sight to deviate from the relative positions necessary to maintain single binocular vision for a given distance of fixation”. Orthophoria occurs when the visual axes cross at the object of regard in the absence of fusional stimuli. Esophoria is present when the visual axis cross in front of the object of regard and exophoria is present when the visual axes intersect beyond the object of regard. The magnitude of phoria is expressed in prism diopters (ΔD)

1.1.4 Components of vergence and accommodation

Maddox (1893) proposed the aggregate vergence response to be composed of tonic, accommodative, reflex and proximal components. Tonic vergence represents the baseline tonic innervation to the extra ocular muscles and shifts the eyes from an anatomic resting position to a more convergent physiological position of rest (Owens & Liebowitz., 1980; Rosenfield, 1997). Accommodative vergence refers to the change in vergence initiated by changes to the blur-driven accommodation (Alpern et al., 1959). Disparity vergence also called fusional vergence responds to the presence of retinal disparity (Stark et al., 1980) and the proximal component is the amount of vergence attributed to the knowledge or awareness of a near target (Hofstetter, 1942).

Similar to the vergence response by Maddox (1893), Heath (1956) classified accommodation into four components: reflex (driven by blur), disparity (induced by changes to fusional vergence), proximal (awareness of a near target) and tonic (due to the tonicity of the ciliary muscle). Although blur is considered to be the primary stimuli for accommodation (Phillips & Stark., 1977), the accommodative response can also be elicited by changes to disparity (Fincham et al., 1957), perceived distance (Hofstetter, 1942) and tonicity of the ciliary muscle (Owens & Liebowitz., 1980).

1.1.5 Interactions between accommodation and vergence (AV and VA)

As mentioned in the previous section, the accommodative and vergence system interact with each other through cross-links in which optically stimulated accommodation evokes convergence (called accommodative vergence or AV) (Alpern et al., 1959; Morgan, 1944) and disparity stimulated vergence evokes accommodation (called vergence accommodation or VA) (Fincham & Walton., 1957; Kent, 1958; Morgan, 1968). The outputs of accommodative vergence and vergence accommodation are defined in terms of AV/A (commonly called as AC/A) and VA/V ratios (commonly referred as CA/C) respectively.

The magnitudes of AV/A ratio can be estimated by isolating accommodation from vergence (occluding one eye) and estimating the magnitude of change in vergence associated with a unit change in accommodation. The AV/A ratio can be quantified using two methods: The stimulus AV/A ratio and the response AV/A ratio. In the stimulus AV/A method, the measured AV is divided by accommodative stimulus value without measuring the actual change to the accommodative response. The stimulus AV/A ratio are reported to be 4 ± 2ΔD /1D (Alpern et al., 1956) in subjects with normal sensorimotor system. This ratio is commonly used in clinical settings for the sake of expediency. In comparison, the response AV/A ratio is obtained when the accommodative response is measured. This ratio is usually higher than the stimulus

AV/A ratio by approximately 8% (Alpern et al., 1956) as a result of the lag of accommodation (Accommodative response < Accommodative stimulus).

Vergence accommodation (VA) is defined as the amount of accommodation elicited by the synkinetic link from vergence system and can be measured by eliminating any stimulus for accommodation. The amount of change in the vergence accommodation per unit change in vergence is called as the VA/V ratio. This ratio can also be represented as a stimulus and a response measure. The stimulus VA/V ratio denotes the change in accommodation per unit change to the stimulus vergence whereas the response VA/V ratio indicates the actual change in the vergence response. The difference between the stimulus and response VA/V is small because the error in the vergence response is small (Ogle, 1950)

1.1.6 Static dual-interactive model of accommodation and vergence system

Several control theory models have been used to describe the feedback driven closed loop response of accommodation and vergence. A schematic of one of the current models of accommodation and vergence (Hung & Semmlow., 1980; Schor & Kotulak., 1986; Schor, 1992) is provided in Figure 2

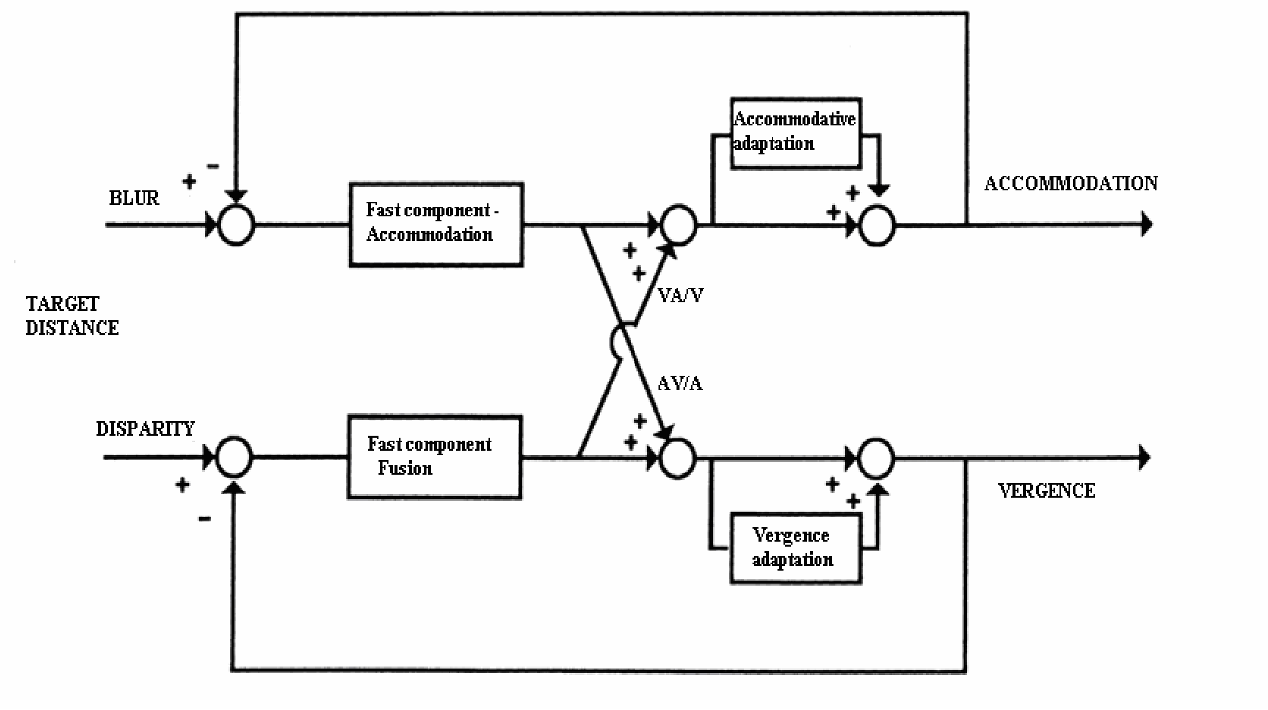


Figure 2: Static dual interactive feedback model (adapted from Schor., 1992)

The static model (Figure 2) describes accommodation and vergence as blur driven and disparity driven systems both controlled by negative feedback loops and interconnected through cross-links (AV and VA). The responses obtained from the ocular motor systems in the presence of visual feedback (blur or retinal disparity) are termed as *closed-loop accommodative/vergence response*. On the other hand, the responses that are independent of visual feedback (feedback loop non-operational) are termed as *open-loop accommodation / vergence responses*. The phasic controller (fast component - Figure 2), responds to changes in stimuli and provides input for cross-link interactions (AV or VA) so that accommodative controller could initiate a vergence response (accommodative vergence or AV) and conversely, vergence controller could initiate an accommodative response (VA or convergence accommodation). The response produced by the controller and the crosslink are summed up in the summing junction where the tonic input feeds in.

The overall accommodative and vergence response is thus a sum of output from the phasic (fast component), cross-link and the tonic components and is finally fed into the plant (crystalline lens via ciliary muscle and zonules for accommodation and extra ocular muscles for vergence) for eliciting the total accommodative /vergence responses. The error (stimulus-response) is fed back into the respective systems through the negative feedback loop in order to keep the system functioning over a prolonged period of time (Ciuffreda & Kenyon., 1983; Schor, 1980).

1.2 Common applications of near addition lenses

1.2.1 Near addition lenses for convergence excess

The commonest application of near addition lenses in pre-presbyopic individuals is towards the treatment of patients with convergence excess. The prevalence of non-strabismic convergence excess has been reported to be 4.5% in a clinic population of symptomatic patients (Lara et al., 2001) and 1.5% in population of university students (Porcar & Martinez-Palomera., 1997). Convergence excess is defined as a condition characterized by a greater magnitude of esophoria at near than at distance (at least by 3 PD) (Duane-White classification, extended by (Tait, 1951). The chief characteristics of convergence excess includes: high AV/A (accommodative vergence/ accommodation ratio), significant lag of accommodation and reduced negative fusional vergence (Scheiman & Wick., 1994b). Non-strabismic convergence excess is usually caused by excessive accommodative vergence innervation as indicated by the high AV/A ratio (Borish, 1975; Scheiman & Wick., 1994b).

The goal of treating an accommodative and or a vergence dysfunction (for e.g. convergence excess) is to relieve ocular symptoms associated with these disorders. Near addition lenses have been considered as a popular option for treating convergence excess because, these lenses would reduce both the vergence as well as accommodative dysfunctions. The addition of plus lenses would decrease the demand on accommodation and reduce the amount of the esodeviation by reducing accommodative vergence through the AV (accommodative vergence) crosslink. Since AV/A ratios are higher in such patients, the addition of low powered plus lens would result in a significant change in binocular alignment. The near add may be determined by measuring the AV/A ratio and prescribing the amount of plus lens power that significantly reduces or eliminates the near esophoria. For example if a patient has a distance esophoria of 1ΔD and near esophoria of 10ΔD with an AV/A ratio of 8ΔD:1D, then a significant reduction in esophoria would occur if (s) he is prescribed with a low power plus lens of 1D. The reduction of eso deviation would reduce the need for compensatory negative fusional vergence. Near addition lenses, in the form of bifocals have been reported to successfully reduce the esodeviation in patients with high AV/A ratios (Jacob et al., 1980; von Noorden et al., 1978). In addition to reducing the vergence dysfunction, these lenses would also eliminate accommodative dysfunction by reducing the lag of accommodation.

1.2.2 Near addition lenses for near-point visual stress

Comfortable and efficient performance of near tasks requires accurate accommodation and vergence responses that can be sustained over a prolonged period without fatigue. The presence of accommodation or vergence disorders result in ocular discomfort which reduces near visual performance (Grisham et al., 1993; Grosvenor, 1977; Simons, 1993). Gruning (1985) points out that near point stress causes various functional vision problems like accommodative insufficiency, ill-sustained accommodation and vergence disorders.

Behavioral scientists believed that the disorders of accommodation and vergence are a result of the sustained stress caused to the visual system due to excessive near work. The Skeffington model (cited from Birnbaum, 1993) proposed that the visual system is biologically unsuited for the sustained near vision demands and believed that sustained near work causes a tendency for convergence to localize closer than accommodation. He postulated that the mismatch between convergence and accommodation resulted in symptoms such as blur and double vision. Birnbaum (1985) attributes the mismatch to the general stress, mental effort and information processing involved during near work. He postulates that sympathetic activation of autonomic reflexes inhibits accommodation exerting a cycloplegic effect which in turn causes over-convergence due to the increased accommodative effort needed to match the accommodative demand. Near point visual dysfunction was thus considered to be due to the mismatch between the two effector systems and it was believed that the application of plus lenses at near would reduce the accommodative demand and associated over convergence so that focus and alignment localize in the same plane.

The prescribing of near adds have been successful in patients accommodative/vergence disorders. For example, these lenses have been shown to reduce asthenopia in patients with accommodative insufficiency. Daum (1983) reported that 15 of 17 patients with accommodative insufficiency experienced at least partial relief and 9 patients experienced total alleviation of symptoms when they were prescribed with addition lenses for near work. In addition to relieving symptoms associated with near point visual dysfunction, these low powered plus lenses (0.25 to 0.75D) have been observed to significantly increase the reading rate and visual performance in 24 visually normal adult subjects (Greenspan, 1975; Pierce, 1980).

1.2.3 Near addition lenses for myopia

Myopia, or nearsightedness, occurs with a general population prevalence as high as 25% in the United States (Sperduto et al., 1983) and 40 to 60% in Asia (Au Eong et al., 1993b; Saw et al., 2002). The dictionary of visual Science (Hofstetter & Griffin., 2000) defines myopia as “a refractive condition in which parallel rays of light entering the eye, with accommodation relaxed, focus in front of the retina”. The onset and progression of myopia have been associated with both genetic (Keller, 1973; Sorsby et al., 1966) and environmental factors (Young, 1955; Young, 1961; Young et al., 1970). One of the older theories of emmetropization, the use-abuse theory (attributed to Cohn, 1886 cited by McBrien & Barnes., 1984) suggests that myopia develops from excessive near work leading to the inability of the eyes to relax accommodation to the far point. Lines of support for environmental influence in the form of excessive near work come from epidemiological studies indicating increasing prevalence of myopia with increasing education and higher amounts of near work (Au Eong et al., 1993a; Grosvenor, 1970; Parssinen, 1987; Rosner & Belkin., 1987)

Ever since near work was considered to be an important factor for the progression of myopia, clinicians have prescribed plus lenses in an attempt to reduce near stress by controlling accommodation (Goss, 1986; Greenspan, 1981; Oakley & Young., 1975). However, more recently, the rationale towards the prescription of these lenses has been to eliminate the hyperopic defocus that might trigger axial elongation of the eye (Gwiazda et al., 2003). Evidence for alteration of eye growth due to changes to retinal image quality originates from animal models that show axial elongation in response to hyperopic defocus (Irving et al., 1992; Schaeffel et al., 1988). In humans, empirical evidence for the presence of hyperopic defocus causing axial elongation in the retina are derived based on studies reporting excessive lags of accommodation in myopic children compared to emmetropes (Gwiazda et al., 1993; Gwiazda et al., 1995a). It was also reported that progressive myopes exhibit greater lag of accommodation than their stable counterparts at high accommodative demands (Abbott et al., 1998; Gwiazda et al., 1995a). Based on this evidence it was postulated that reduction or elimination of the excessive lag of accommodation would attenuate the progression of myopia in myopic children (Gwiazda et al., 2003)

Several clinical trials have been conducted in order to evaluate the ability of near addition lenses in slowing myopia progression. The results of these studies have not been consistent ranging from no success (Grosvenor et al., 1987), limited success (Gwiazda et al., 2003) and successful reduction of myopia (Leung & Brown., 1999; Oakley & Young., 1975). However, even those studies that showed an overall insignificant treatment effect, exhibited greater reduction of myopia in children with esophoria when the data were re-analyzed with respect to baseline near phoria (Goss, 1994). Similar results showing higher benefits of plus lenses in esophoric children have been reported by (Fulk et al., 2000).

In addition to the near phoria, the accommodative response also seems to determine the success of near addition lenses. So far, only one group (COMET study group - Gwiazda et al., 2004) has performed a comprehensive evaluation of the influence of both accommodative responses as well as near phoria on attenuating myopia progression with progressive addition lenses. In their analysis, the COMET study group (Gwiazda et al., 2004) observed greatest reduction of myopia in children having higher lags of accommodation and near point esophoria. This finding along with supportive evidence from previous studies (Fulk et al., 2000; Goss, 1994) suggests the importance of near phoria in the mechanism of reduction of myopia with near addition lenses.

1.3 Oculomotor response to near addition lenses

1.3.1 Effect on Accommodation

Since the basis for prescribing plus lenses have been to control accommodation and thereby the accommodative vergence, many researches have investigated the precise effect of these lenses on ocular accommodation (Easwaran, 2005; Rosenfield & Carrel., 2001; Seidemann & Schaeffel., 2003; Shapiro et al., 2005) Accommodative responses were measured under both binocular and monocular viewing through different magnitudes of plus lenses ranging from +0.75D to +3.00D in pre-presbyopic adult participants. Table 1 provides a summary of results obtained in these studies. The results of these investigations consistently show that near addition lenses reduce the lag of accommodation with lower dioptric power (+1D) and even reversed its direction producing a lead of accommodation with higher dioptric powers (+2 and +3D).

Study	**STA (D)**	**Accommodative error index**							
		No add		**+1D**		**+2D**		**+3D**	
		B	**M**	**B**	**M**	**B**	**M**	**B**	**M**
Seidemann (2003)	3D	-0.12 ± 0.45D	-0.29 ± 0.35D	0.25 ± 0.44D	0.02 ± 0.32D	0.77 ± 0.46D	0.39 ± 0.26D	Not done	Not done
Shapiro (2005)	3D	-0.03 ± 0.3D	-0.08 ± 0.2D	Not done	Not done	0.90 ± 0.3D	0.65 ± 0.3D	1.32 ± 0.4D	1.12 ± 0.35D
Easwaran (2005)	3D	-0.55 ± 0.14D	Not done	0.05 ± 0.08D	Not done	0.64 ± 0.06D	Not done	Not done	Not done

Table 1: Comparison of accommodative errors observed with different magnitudes of addition lenses in various studies.

Plus sign indicates lead of accommodation and minus sign indicates lag of accommodation. B refers to binocular viewing condition and M refers to monocular viewing condition. The lags of accommodation observed without addition lenses were consistently seen to reduce with lower magnitude plus lenses and produced lead of accommodation with higher dioptric powers. The differences between binocular and monocular focuses can be seen to increase with higher magnitude addition lenses suggesting a possible role of convergence accommodation.

It can also be seen from the above table that the differences in accommodative error between the viewing conditions (that represents convergence accommodation) is quite low without any additions lenses. However, with increasing magnitudes of addition lenses, the difference between the two viewing conditions also tend to increase with greater over focus in the binocular viewing condition suggesting a presence of increased convergence driven accommodation. The possibility of increased VA (mediated by changes to the vergence system) has however not been directly investigated by any of these studies.

1.3.2 Effect on Vergence

The earlier studies evaluating the effect of near addition lenses mentioned in the previous section have mostly considered accommodation alone but not the complete binocular response which would include vergence as well as accommodation. Vergence and accommodation are tightly coupled where changes in accommodation can cause changes in the vergence response through the accommodation driven vergence (AV) cross-link (Alpern et al., 1959) and vice-versa for vergence driven accommodation (VA) (Fincham & Walton., 1957). The introduction of near addition lenses reduces the demand on accommodation leading to a reduction in accommodative convergence thereby inducing a relative exophoric shift. This divergence, through negative feedback mechanism would trigger an increase in the convergence through the disparity vergence controllers. However, over time, vergence adaptation would occur thus reducing the overall vergence error and the demand on the fusional vergence controller.

1.3.3 Vergence adaptation- Definition and mechanism

Schor (1979a) proposed the fusional (disparity) vergence to be composed of two components; a fast fusional component which aligns the eyes within 1 sec in response to retinal image disparity and a slow fusional component that acts to maintain the alignment. The slow fusional component receives its input from the fast component and by means of negative feedback reduces the demand on the fast fusional vergence system. Figure 3 illustrates a computer stimulation of complete vergence adaptation when known magnitudes of prisms are placed in front of the eyes.

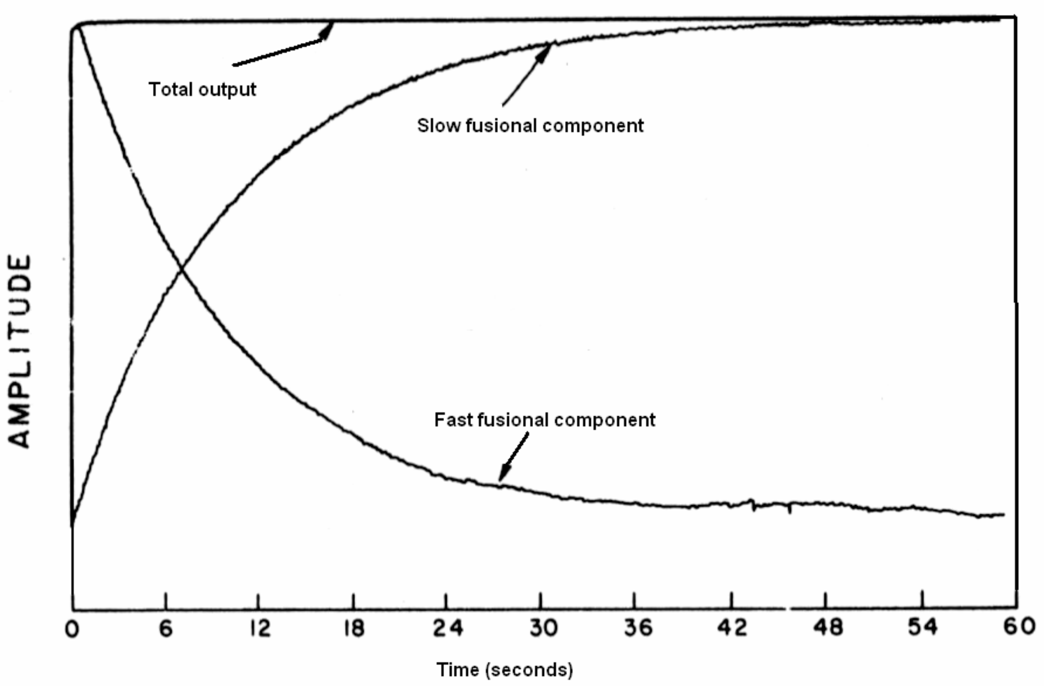


Figure 3: Illustration of complete prism adaptation

The above figure shows the respective outputs of fast and slow fusional components over time. The output of slow fusional component can be seen to increase over time with a subsequent reduction in the output of fast fusional component yet maintaining a constant aggregate response. (Reprinted with permission from Schor (1979a); Relationship between vergence eye movements and fixation disparity, Vision Research 19(12} 1979 © Elsevier).

The above figure shows the relation between the fast and the slow fusional components. The total fusional output can be seen to be initiated by the fast component initially, but as the vergence stimulus is maintained over time, the sustained output of fast fusional component will initiate the slow fusional vergence. The output of slow fusional vergence would subsequently allow for a reduction of the fast fusional output through a negative feedback mechanism yet maintaining the total vergence output and allowing the fast fusional component to respond to subsequent disparities. Thus when the vergence stimulus is maintained over time, the majority of the response is mediated through the slow fusional controller. If the fusional vergence is eliminated at this point (through dissociation) the phoria measured through the prism would be similar to baseline due to the longer decay time constant of the slow fusional vergence. This apparent reduction of phoria that actually reflects the prolonged rate of decay of slow fusional vergence (Schor.,1979a) has been termed vergence adaptation (synonyms - phoria adaptation, prism adaptation)

1.3.4 Vergence adaptation to ophthalmic lenses

Adaptation to prism induced disparities has been extensively studied (Carter, 1963; Carter, 1965; Ellerbrock, 1950) and reported in the literature. However, very few investigations have studied vergence adaptation to lens induced heterophoria. Ophthalmic lenses alter vergence through the accommodation vergence (AV) cross-link (Alpern et al., 1959). Schor (1979b) monitored adaptation to plus lenses by recording vergence eye movements using an infrared monitor for brief periods of binocular viewing. Three subjects were instructed to view a vertical line target at a distance of 50 cm through +2.00D lenses and eye movements were recorded after 5s and 60 s of binocular viewing. These lenses were reported to induce exophoria but no adaptation was seen after 5 s of binocular viewing. However, after 60s of binocular viewing the exophoria had either partly or totally reduced indicating partial or total adaptation of the slow fusional vergence.

North and Henson (1985) performed a more elaborate investigation on the adaptive ability of heterophoria with both negative and positive lenses. Vergence adaptation was evaluated in 4 adult subjects at a near fixation distance of 40 cm. Heterophoria was measured every 15 sec for the first 3.5 minutes, after 33.5 min and 66.5 minutes of binocular viewing. Adaptation to +2D lenses was found to vary among their 4 subjects and their rates of adaptation were seen to depend on the magnitude of the induced exophoria (see Table 2).

Subjects	**Exophoria induced due to +2D lenses (ΔD)**	**Magnitude of adaptation (in %) following binocular viewing for**	
		3.5 min	**66.5 min**
1	7.0	43	71
2	8.75	40	63
3	5.5	55	86
4	10	48	60

Table 2: Magnitude of adaptation to lens induced exophoria at a fixation distance of 40cm (adapted from North and Henson 1985)

The most rapid reduction in exophoria occurred within 3.5 minutes of binocular viewing (Mean adaptation 46.3%) with further gradual reduction to 70% over 66.5 minutes of binocular viewing. The authors however, measured changes to phoria alone and did not evaluate the changes to the accommodation system which initiated the vergence adaptation through the AV cross link. According to the accommodative-vergence model proposed by (Schor & Kotulak., 1986; Hung & Semmlow., 1980), adaptation of the vergence system would reduce the VA cross-link because the cross-links interactions are located before the tonic component (see Figure 2). However, another model proposed by Ebenholtz & Fisher (1982) and supported by Rosenfield & Gilmartin (1988b) predicted no change with vergence adaptation since their model places the cross-links after the tonic component. Rosenfield and Gilmartin (1988b) evaluated the effect of vergence adaptation on convergence accommodation by inducing convergence with 6ΔD Base-out prisms. The authors measured convergence accommodation and phoria with and without 6ΔD when participants performed a near task at 33 cm for 3 min. Vergence adaptation occurred with a significant reduction in exophoria; however, vergence accommodation did not show any significant reduction with vergence adaptation. The authors thus suggested that convergence accommodation does not reduce with adaptation of the induced phoria. However, they did not measure changes to tonic accommodation which could have masked the changes to vergence accommodation if accommodative adaptation occurred.

Schor's model of accommodation and vergence interactions (Schor & Kotulak., 1986; Schor, 1992) is supported by the empirical evidence of Jiang (1996) who observed a reduction in accommodative vergence following adaptation to the accommodative system. This indicates that the position of cross-links should be before the tonic component and not after as suggested by Ebenholtz & Fisher (1982). Hence based on Schor's model (Schor & Kotulak., 1986; Schor, 1992) and Jiang's experimental evidence (Jiang, 1996) one would predict a similar response in the vergence system wherein adaptation of the vergence system would reduce the convergence driven accommodation. This reduction might decrease the initially increased binocular focus seen in studies that evaluated accommodative response with addition lenses.

1.3.5 Factors influencing Phoria adaptation

1.3.5.1 Magnitude of adapting stimulus

The effect of varying magnitudes of prism induced disparities have been studied by several authors (Ogle, 1950; Sethi & North., 1987) who report prolonged rate of adaptive decay but greater magnitude of adaptation with larger adapting stimuli. However, the disparity induced by the introduction of a prism is different from that induced by the addition of an ophthalmic lens because the latter is influenced by the individuals AV/A ratio. For example, introduction of +2D lenses would result in an exophoria of 10ΔD in one individual with 5:1 AV/A ratio and only 6ΔD in a different individual with a ratio of 3:1, despite the same magnitude of near addition lens used.

North and Henson (1985) reported an inverse relationship between the rate of adaptation and the amount of induced phoria (see Table 2 for results). Individuals with larger induced phorias (subject 2 and 4 in Table 2) did not show complete adaptation even after 1 hour of binocular viewing. The authors did not offer any explanation for this finding. If vergence adaptation is considered as a process which serves to maintain sustained single and clear binocular vision without excessive fatigue, then the incomplete adaptation observed in the individuals with larger induced phoria could be explained by changes in the accommodation system. North and Henson (1985) only evaluated the vergence response and did not measure the accommodative response with and without addition lenses. Therefore little is known about the influence of the accommodative response on vergence adaptation in individuals with different AV/A ratios.

1.3.5.2 Age and Vergence adaptation

Although vergence adaptation (especially to prism induced disparities) has been studied extensively in pre-presbyopic adults, relatively few investigations are available about the vergence adaptive ability of children. Wong et al (2001) compared vergence adaptation between children (N=18; mean age = 9.8 years) and young adults (N=18; mean age 25.8 years) to a prolonged near task (reading at a distance of 15 cm for 5 minutes) and concluded that vergence adaptation was significantly greater in children than in adults (Mean magnitudes of adaptation: Children =0.45MA and adults=0.11MA). The greater adaptation seen in children was attributed to higher baseline tonic vergence observed in this group. An abstract by Owens et al (Owens et al., 1991) reports on both accommodative and vergence changes under similar experimental condition. Vergence adaptation was studied in 18 young adults and 20 children after a 20 minute near task at a distance of 16.5 cm. No significant task induced adaptation in either ocular motor system in either study group was found. Currently there is no conclusive evidence regarding possible differences in the adaptive abilities of the vergence system between children and adults.

2 THESIS OBJECTIVES

Previous evidence indicates that plus lenses reduce the lag of accommodation and results in greater differences between binocular and monocular focus. These lenses have been found to induce exophoria which reduces over time. To date, a complete evaluation of the binocular motor response has not been conducted to investigate the precise relationship between the changes to the accommodative and vergence systems during sustained binocular viewing with near addition lenses. Additionally, we would also like to determine whether the magnitude of the adapting stimulus or age has any influence on vergence adaptation in response to near addition lenses.

In summary, this thesis will aid in better understanding of the mechanism outlining changes to the accommodative and vergence systems by answering the following questions:

1. Does the increase in binocular accommodation parallel the increase in exophoria induced by near adds?
2. Does vergence adaptation reduce the over-driven binocular focus?
3. Does the magnitude of adapting stimulus (AV/A) influence the adaptation response?
4. Does age have an effect on vergence adaptation to near addition lens?

3 INSTRUMENTATION AND METHODS

3.1 Measurement of Accommodation

3.1.1 PowerRefractor and its operating principle

In the current investigation, accommodative responses were measured using a PowerRefractor (Figure 4). The PowerRefractor (MultiChannelSystems, Reutlingen, Germany) is an infra-red optometer that works on the principal of eccentric photo refraction (Bobier & Braddick., 1985; Howland, 1985). The advantages of this technique over conventional techniques like retinoscopy are its remote testing distance (1 Meter) and its ability to obtain faster measurements. These factors make the PowerRefractor useful in refracting infants and young children.

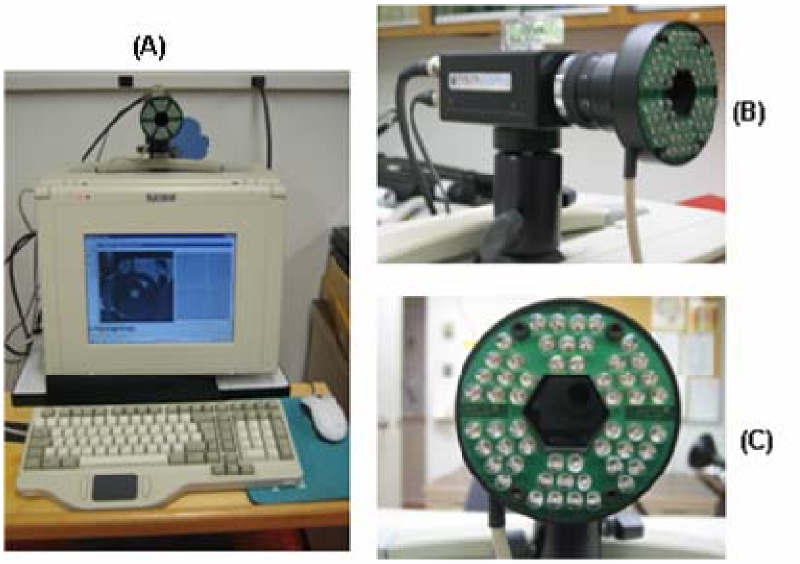


Figure 4: Picture of the PowerRefractor (Multichannel Co, Reutlingen, Germany)

The Power Refractor (Figure 4a) consists of a photorefractor with six light emitting diodes (LED) segments (Figure 4c) each containing nine infra-red LED's arranged around a CCD camera (Figure 4b) connected to a portable personal computer. This arrangement of LED's has been shown to increase the working range of the instrument and also to reduce monochromatic aberration compared to a single source of light (Roorda et al., 1997). In this technique, infra-red light from the extended eccentric light source returns back to the CCD camera after reflection from the eye. The estimate of optical defocus is determined from the intensity profile across the pupil obtained in the image of the camera (Bobier & Braddick., 1985). The slope of the intensity profile varies with the eye's defocus and this information is converted into refractive error or accommodation based on an inbuilt calibration equation (Bobier & Braddick., 1985).

3.1.2 Measurement modes of the Power Refractor

The PowerRefractor has a sampling rate of 25 Hz (can measure accommodation every 0.04sec) and functions in five different measurement modes namely, binocular, monocular, fast-screening, complete refraction and 3D reconstruction. Out of these 5 modes, continuous measures of accommodation are possible through the binocular and monocular test modes. Both the settings provide information on the accommodative response along the vertical ocular meridian coupled with measures of pupil diameter and gaze deviation. Estimates of pupil size and gaze position are made using a contrast detection algorithm to locate the pupils and the first purkinje image. Deviations in gaze position are identified using a Hirschberg ratio of 11.82 (Barry & Backes., 1997) (i.e. 1 mm displacement of corneal reflex is produced when the eye rotates by 11.82 degrees).

In the current study, *monocular mode* was used to measure accommodation in all participants. A screen dump of the "monocular mode" is shown in Figure 5. This mode was preferred over the binocular mode because it provides the advantage of tracking the participants gaze while recording the measurements (Figure 5-Section 1). The binocular mode provides the same information about gaze deviation, but only after data collection. This feature of the *monocular mode* is extremely useful to ensure proper fixation at the target especially in children due to their limited attention span.

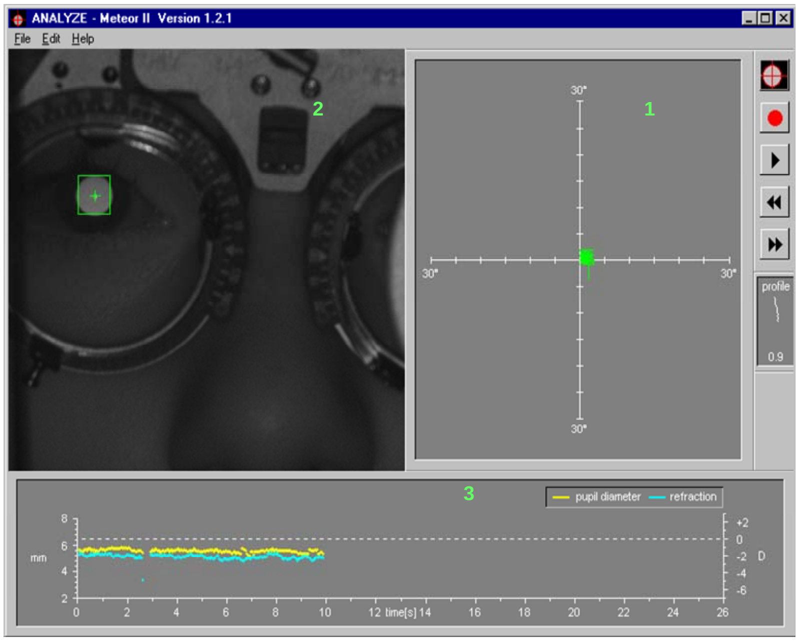


Figure 5: PowerRefractor interface using a Monocular measurement mode.

Section 1 (outlined on top right corner) represents the gaze tracker which identifies deviation in gaze positions up to 30 degrees with 5 deg separation. Section 2 shows the measured pupillary region whose intensity profile is converted into accommodation response. Section 3 illustrates the accommodation response measured along the vertical ocular meridian coupled with measures of pupil diameter over a 10 sec period.

3.1.3 Calibration of PowerRefractor

A calibration study is required to determine the accuracy and linearity of the response obtained using PowerRefractor. Although the PowerRefractor has an inbuilt calibration equation for adults it was necessary to determine if this calibration equation was appropriate for all participants enrolled in this investigation. Additionally, it is expected that variations in fundal reflectance characteristics might influence the light distribution in the pupil thus producing variability between individuals (Schaeffel et al., 1993).

A two step calibration process was conducted in all participants (13 children and 11 adults) to ensure the following:

- Absolute accuracy (to estimate whether the accommodative response obtained using the PowerRefractor represents the true response when compared to Retinoscopy)
- Relative accuracy (to estimate whether PowerRefractor provides a 1:1 relationship when the magnitude of stimulus is changed)

Experimental procedure:

Step 1: Absolute Calibration

In order to evaluate the absolute accuracy of PowerRefractor, accommodative responses were measured at two distances (4m and 0.33m) and compared with the responses acquired using the gold-standard retinoscopy. Similar techniques have been adopted by previous studies to estimate the accuracy of the PowerRefractor responses (Blade & Candy., 2006; Seidemann & Schaeffel., 2003)

Participants wore their corrective lenses (determined using subjective refraction) and were instructed to fixate a high contrast target placed at a distance of 0.3M or 4M. Retinoscopy and PowerRefractor responses were determined while the subjects binocularly fixated the targets. The order of estimating accommodative response was randomized between the testing methods and the two testing distances. The "method of agreement" proposed by Bland and Altman (1986) was used to determine the 95% limits of agreement (Mean $_{(diff)}$ ±1.96*stdev $_{(diff)}$) between the two testing methods. In addition, a paired t-test was also performed to compare the responses obtained with the two methods.

Step 2: Relative Calibration

All participants were seated comfortably with their chin positioned on a chin rest in a darkened room 1 meter from the PowerRefractor**.** Participants wore corrective lenses (determined using retinoscopy and subjective refraction) that provided a visual acuity of at least 6/6 in each eye and were instructed to view a high contrast target (placed at 4m) with their left eye. An infrared (IR) filter (Kodak 87B, IR filter, Rochester, NY) was placed in front of the right eye which blocked visible light but permitted the IR light source of the PowerRefractor to obtain measurement. Series of positive and negative ophthalmic lenses (+4D to -1D in 1D step) were added over the IR filter to induce refractive errors ranging from -4 to +1D. The resulting PowerRefractor measure (Y) was assessed for each lens and was plotted as a function of induced refractive error (X). Linear regression analysis was performed to estimate the relationship between induced and measured refraction obtained using the PowerRefractor.

RESULTS

Step 1: Absolute calibration

Figure 6a shows the accommodative responses obtained using retinoscopy and PowerRefractor at the two viewing distances. It can be seen that the mean accommodative response obtained using the PowerRefractor were on an average more hyperopic at both viewing distances (Bias = 0.26D at distance and 0.22D at near; P=0.001). This lower response would result in an underestimated accommodative response at a near when measurements are obtained with the PowerRefractor.

Figure 6b compares the individual accommodation responses obtained using both the methods on a Bland and Altman plot. It is evident from the figure that 10 out of 12 participants showed a small hyperopic offset in the PowerRefractor response when compared to the retinoscopy.

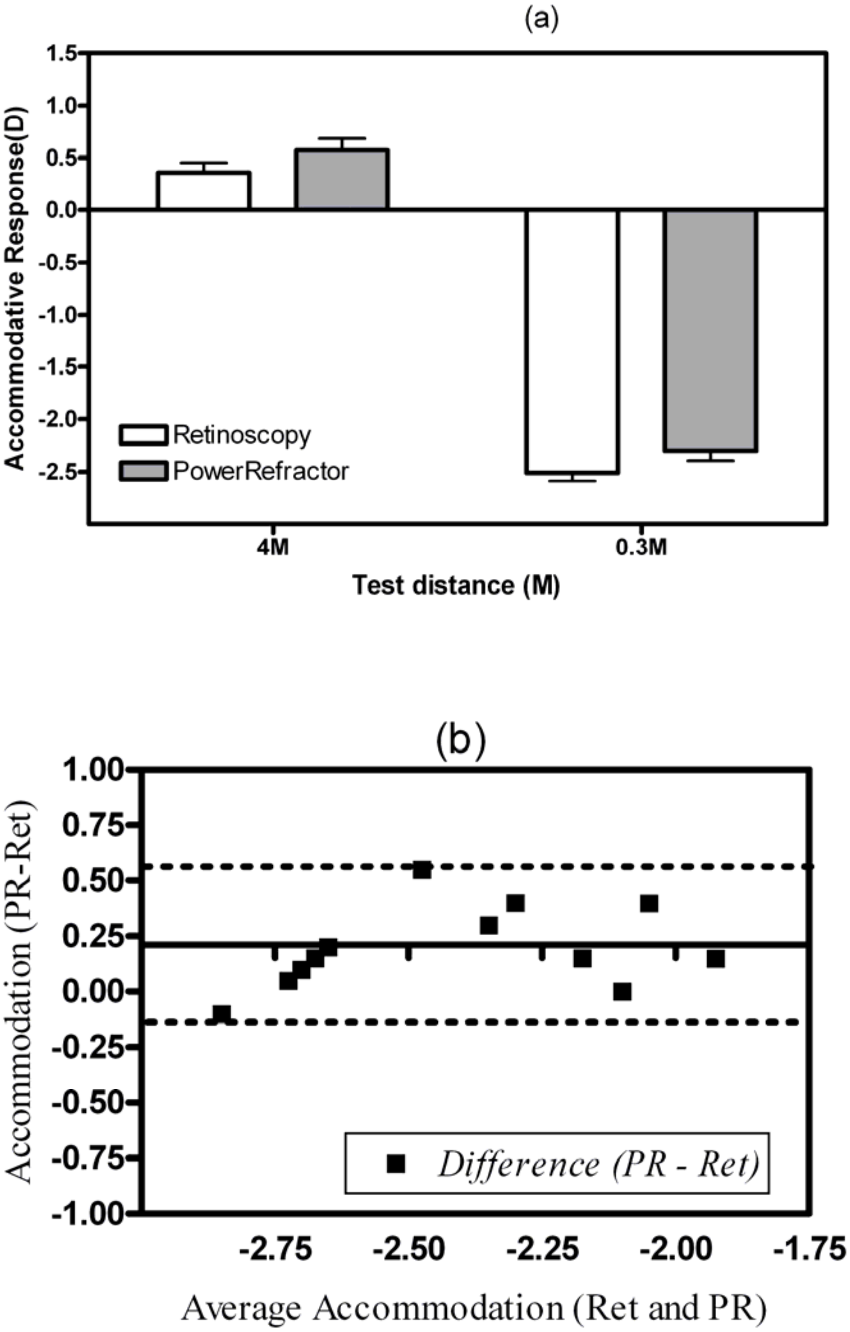


Figure 6: Absolute calibration of PowerRefractor

Figure 6 (a-Top): - Comparison of accommodation response with PowerRefractor and retinoscopy at two different distances indicates that the PowerRefractor on an average provides a more hyperopic response than the retinoscope. Figure 6 (b-bottom) shows a plot of average accommodation response obtained using the two methods vs. difference between the two methods at a fixation distance of 0.3M. The solid line indicates the average bias (0.24D) observed between the two methods. A trend towards a more hyperopic response can be seen in majority of the participants for the 0.3M viewing distance. A similar trend towards hyperopic estimation was observed for the 4M distance as well.

Step 2: Relative calibration

Analysis for the relative calibration was performed after subtracting the bias (average=0.24D) observed between the Retinoscopy and PowerRefractor in the absolute validation protocol. Figure 7 shows the results of regression analysis performed on both adult and child participants (Regression equations, Child: Y= 1.07 X +0.25; Adult: 1.02X+0.27). It can be seen that the slopes of linear fit for both the study groups were close to 1 with an intercept close to 0.25D in either groups. Neither the slopes nor the intercepts were found to be significantly different between the two study groups (Slopes: F=0.98; P = 0.32 and Intercepts: F=1.17 and P = 0.28). Thus a pooled equation (Y = 1.05X + 0.25) was determined for calculating the accommodation response for both the groups.

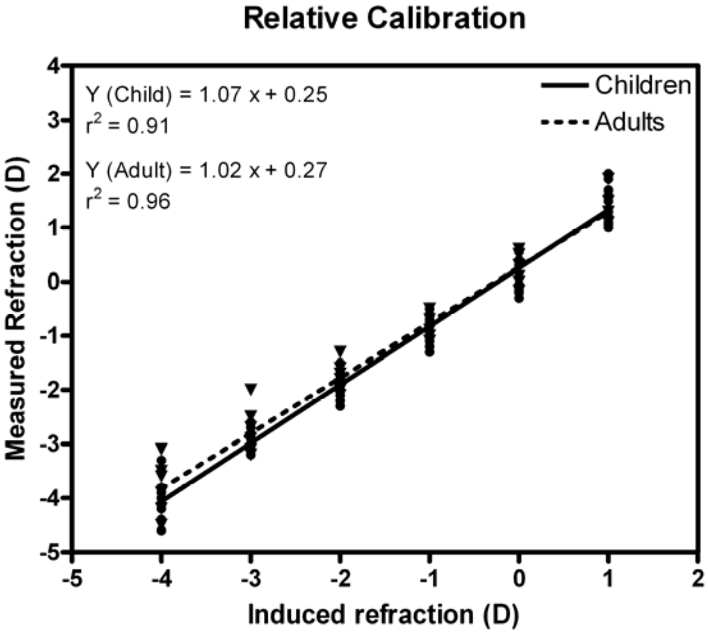


Figure 7: Relative calibration of PowerRefractor

Linear regression analysis of measured refraction and induced refraction shows a slope close to 1 with no significant difference between the slopes of adults and children.

Conclusions

The absolute validation protocol showed the PowerRefractor to have a small hyperopic offset of 0.25D, similar to previous studies (Abrahamsson et al., 2003; Allen et al., 2003) suggesting that the true response would be less hyperopic or more myopic than the values that are obtained. Relative calibration showed a slope of 1.05 within the tested range indicating that a change in accommodative stimulus by 2D (equivalent to the reduction in stimulus produced by a +2D lens) would produce a change of 2.1D.

Thus in the current investigation, the true accommodation response (assuming retinoscopy provides an accurate measure) was determined by substituting the accommodative responses obtained using the PowerRefractor into the regression equation (True response = (PowerRefractor response /1.05) - 0.25). For example if the PowerRefractor provides an accommodation response of - 2.5D, the true response was determined to be -2.63 D using the above equation.

3.1.4 Targets for measuring and sustaining closed loop accommodation

Two near targets, namely a fixating target and a measuring target were developed for sustaining fixation and for the measurement of closed-loop accommodation respectively. Near fixation was sustained at the desired target distance (33 cm) by instructing participants to watch a cartoon movie. Accommodation was measured at frequent intervals with a colored picture target (measuring target). The use of a separate measuring target (instead of the movie) was necessary to maintain the same stimulus characteristics (target size, brightness and contrast) every time accommodation was measured.

Both the near targets were displayed onto a miniature liquid crystal display (LCD) monitor (Model No: LT-V18 U; Victor company of Japan) and were viewed at a distance of 33cms through a semi-silvered mirror (Details in section 4.4-Experimental setup). The monitor was 1.77″ wide, subtended 3.5 deg x 2.3 deg (H x V) and enabled the gaze deviations to be kept within 5 degrees of fixation thus preventing any significant off axis measurements that might result in erroneous measures of the accommodative responses (Millodot & Lamont., 1974).

3.1.4.1 Fixating target

The near fixating target consisted of a cartoon movie (The Three musketeers, Walt Disney Productions) played using a digital video disc (DVD) and displayed on the miniature LCD monitor. This target was preferred to a high contrast reading text in view of the shorter attention span anticipated in young children. Similar near fixation tasks other than high contrast text have been used in previous studies to test the effects of near work on accommodation (for e.g. video game- Gwiazda et al., 1995b). A cartoon movie is an interesting stimulus for sustaining fixation especially for young children and represents natural viewing conditions. However, the disadvantages of such stimuli are: changes in perceived size, brightness and emotional extent that might exist within each frame. Two movies (Three musketeers and Scooby-doo), considered to be of interest to children were screened for the above mentioned characteristics. The movie “Scooby-doo” had several frames with extremely bright targets (greater than 80 Cd/m2) and several others with extremely low brightness (less than 10 cd/m2). In the movie “Three musketeers” the overall brightness of the frames was relatively stable and ranged between 30 and 60 cd/m2. In addition, the movie (“Three musketeers”) was a musical comedy and did not have any emotional or scary scenes like the other cartoon movie that was screened for selection. Hence, the movie “Three musketeers” was selected as a fixation target to sustain near fixation, considering the content of the movie and it’s the relative stability in brightness.

3.1.4.2 Accommodative stimulus for measuring target

A colored picture (Figure 8) was used to measure binocular and monocular accommodation at each time point. This target was selected to match the fixating target (movie) as closely as possible and because it would be more interesting and therefore hold the attention better than a standard high contrast text for the younger study group. Although the picture contains lot of interesting information for the viewer the attention of participants was directed towards “Mickey and Minnie’s faces” (approximately 5.5 mm in the LCD display) during the measurement of accommodation. This specification was necessary to ensure stable fixation and thus avoid off axis measurements (Millodot & Lamont., 1974)

Figure 8: Picture used for measuring binocular and monocular accommodation at frequent intervals.

The specified target (faces) had good contrast (85%) and the target luminance was 15 cd/m^2 . The validity of the picture target as an accommodative stimulus was determined by comparing the accommodative response with that obtained using a standard high-contrast text in 11 emmetropic children (Appendix 1). The Bland and Altman technique (1986) was used to determine the 95% limits of agreement between the two targets. It was found that on average participants under accommodated by 0.2 D with the picture target and the 95% limits of agreement ranged between ± 0.5D. Although the average showed a lower accommodative response, the same trend was not consistently seen in all participants (as seen from the plot) with some participants demonstrating greater accommodation with the picture target. Since the picture target had good contrast and exhibited smaller magnitude of difference compared to the standard text, it was considered to be a good stimulus for accommodation.

3.1.4.3 DOG for measurement of open-loop accommodation

A difference of Gaussian target (DOG) of 0.2cpd spatial frequency was used to measure tonic accommodation. Lower spatial frequency DOG targets (less than 0.5 cpd) have been shown to be an insufficient stimulus to drive reflex accommodation as the grating lack contour and edge information (Tsuetaki & Schor., 1987). The target was projected on a 17 inch cathode ray tube (CRT) monitor with edges covered using a black cloth to avoid any contour information. The DOG target used in the current investigation does not stimulate accommodation and has been used in several other studies in the laboratory (Easwaran, 2005; Suryakumar & Bobier., 2004).

3.2 Measurement of Phoria – Modified Thorington Technique (MTT)

Horizontal near heterophoria was measured using the modified Thorington technique (Borish, 1975) at a near testing distance of 33cms. The magnitude of the phoria was quantified using a custom-designed tangent scale which consisted of a small central hole to accommodate the light source and a horizontal row of letters/numbers on either side. The letters/numbers on scale were 3 to 4 mm high, equivalent to a Snellen fraction of approximately 6/15 (at that distance) and each letter/number was separated by 3.3 mm (1ΔD apart at a distance of 33cms). The tangent scale was illuminated using 3 white LED's housed inside a rectangular box providing a background luminance of 10 cd/m^2.

Participants wore their corrective lenses (if needed) and were instructed to fixate the center of the tangent scale and maintain the zero clear during the measurement. An occluder was placed in front of the right eye for 10 sec and a Maddox rod (grooves aligned horizontally) was inserted during the period of occlusion. After 10 sec (following a mental count) the occluder was removed and the participant was instructed to report the number/letter that was closest to the red line. The same technique was repeated 3 times and the near heterophoria was defined as the average of the three responses.

The accuracy of the custom designed scale was evaluated by comparing the MTT measures with an objective - prism neutralized alternate cover test and its repeatability was assessed by repeating MTT measures on a separate occasion (Appendix- 2). The cover-test results showed an overall exophoric bias (approximately 0.5PD) however, this was not found to be statistically significant. The Bland and Altman Technique was used to determine the 95% limits of agreement (Mean $_{(diff)}$ ±1.96*stdev $_{(diff)}$) for both the comparison of the different testing methods and the repeatability of the test. The results show good agreement between MTT and Cover test with 95% limits of agreement ranging between ±1.05 ΔD ($p>0.05$) suggesting that the phoria obtained using MTT will only be 1.05 ΔD higher or lower than the objective estimation with alternate cover test. The Modified Thorington Technique was also found to show good repeatability with a Co-efficient of Repeatability (COR) of 1.98 ΔD indicating that any change in phoria greater than ±2 ΔD would indicate a significant change in the measurement. Similar results (good repeatability and validity) with the MTT have been reported by previous studies (Casillas Casillas & Rosenfield., 2006; Escalante & Rosenfield., 2006; Rainey et al., 1998).

In light of good accuracy, repeatability, its ability to obtain faster measurements and simpler test instructions that can be easily comprehended by a child; the MTT was chosen to measure horizontal near heterophoria in the current investigation.

3.3 Study participants

Eleven adults between the ages of 20 and 29 years (Mean age = 23.2 ± 2.39 yrs) and 13 children between the ages of 7 and 14 years (Mean age = 11 ± 2.34 yrs) were enrolled in the study. Adults were recruited from the students / staff population at the School of Optometry, and children were recruited from the Optometry clinic database at the University of Waterloo. The study was approved and received full ethics clearance from the Office of Research Ethics, University of Waterloo. Informed consent (for adult participants) and parental permission (for children) were obtained before the commencement of the study. All participants with normal general health and not on any medications that might influence the accommodation and vergence systems (Westheimer, 1963) underwent preliminary examination to ensure the following:

- Emmetropic refractive error (defined as a refractive error between -0.5 to +1.0D (Hirsch, 1964)) determined using cycloplegic refraction
- Best corrected visual acuity of 6/6 in each eye
- Normal distance and near phoria based on Morgan standards (Morgan, 1944) determined using alternate cover test
- Normal amplitudes of accommodation for their respective ages determined using push-up technique (Borish, 1975)
- Normal near point of convergence (Scheiman & Wick., 1994a)and
- Anterior chamber angle greater than Von–Herrick grade II to perform cycloplegic refraction.

Baseline characteristics of the study groups are shown in Table 3.

PARAMETER (MEAN ± SD)	**ADULTS**	**CHILDREN**
No of Participants	11	13
Age (yrs)	23.2 ± 2.39 (20-29)	11 ± 2.34 (7-14)
Refractive error (D)	0.1 ± 1.17 (-0.25 to 0.5D)	0.6 ± 0.12 (0.5 to 1D)
Distance Phoria (PD)	-0.11 ± 0.78PD (1 to -1PD)	-0.45 ± 1.1 PD (0.5 to -1PD)
Near phoria (PD)	-3.6 ± 2.2PD (-1 to -6.5PD)	-3.27 ± 2.1PD (-0.5 to -8PD)

Table 3: Demographics of study population

Cycloplegic refraction was performed after non-cycloplegic refraction, binocular vision and anterior segment assessment using 1% tropicamide. (Egashira et al., 1993; Manny et al., 2001). Participants received two drops of 1% tropicamide in each eye with the second drop instilled approximately 4–6 minutes after the first drop. Residual accommodation was calculated twenty minutes after the second drop by objectively measuring accommodative response to high-contrast targets located at 4m and 33cm. The mean residual accommodation was found to be 0.36 ± 0.35D in children and 0.24 ± 0.38D in adults. Cycloplegic acceptance was then performed based on objective auto refraction findings determined using Nikon Retinomax K-plus (Nikon Corporation, Tokyo, Japan).

3.4 Experimental setup and Procedure

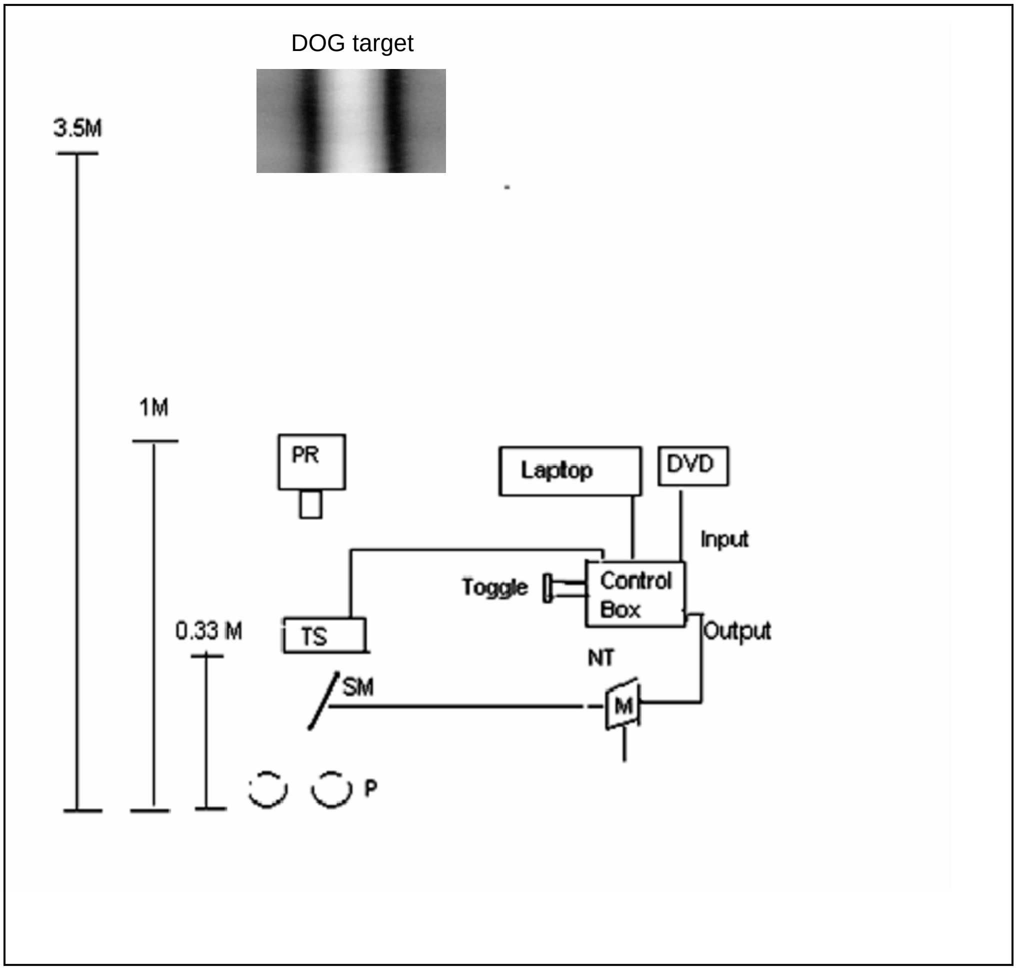


Figure 9: Schematic of the experimental set-up.

The participant (P) was seated at a distance of 1M from the PowerRefractor (PR). The near targets (NT) for accommodation were displayed on a miniature LCD monitor (M) that was projected at a distance of 33 cm using a semi-silvered mirror (SM). The monitor received input from either the laptop or the DVD player and the presentation of targets were controlled using a custom designed control box. In addition to receiving input from the near targets, the control box also received input from the Tangent scale (TS) designed for measurement of near phoria. A Difference of Gaussian (DOG) target was placed at 3.5 M for opening the loop of accommodation.

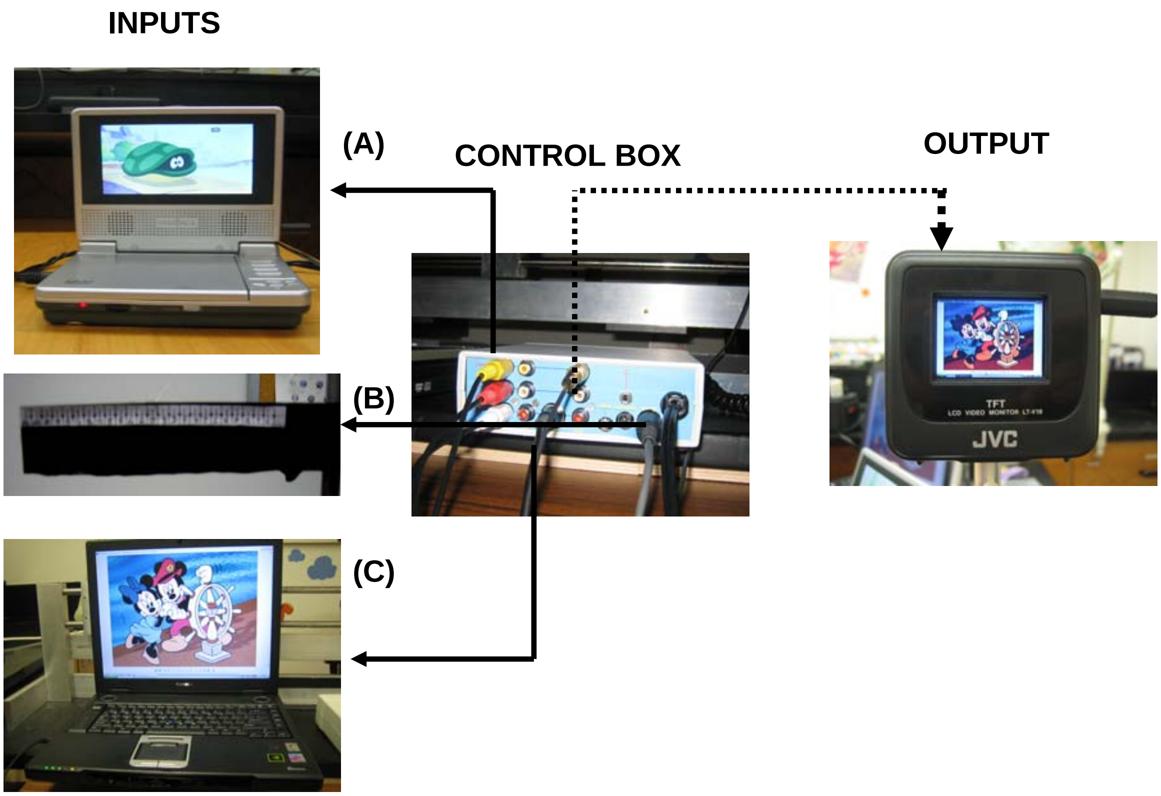


Figure 10: The different inputs and the output of the control box.
(A): Near fixation target- Movie played from a DVD player; (B): Tangent scale to measure near phoria; (C): Near measuring target- Coloured picture target loaded on a laptop. The output from the sources is displayed on a miniature LCD monitor.

A schematic of the experimental setup is shown in Figure 9. The outputs of the two near targets as well as the tangent scale were fed into the custom designed control box (Figure 10). This arrangement was necessary because the current investigation evaluates influence of changes in accommodation on vergence and vice-versa and it is imperative to be able to change targets for measurement of either parameter quickly. The control box was designed with a toggle key which facilitated the rapid change of targets. The order of the presentation of targets is summarized below:

By default, the LCD monitor received its input from the fixating target (movie)

- Toggle 1: The display on the LCD monitor would go blank and the tangent scale would be illuminated for measurement of heterophoria.
- Toggle 2: LCD display changed from blank screen to the measuring target (colored picture) for measurement of accommodative response.
- Toggle 3: Display changed from measuring target to fixating target (movie) for sustaining accommodation under binocular viewing condition.

3.4.1 Experimental Procedure

The experimental procedure consisted of two study sessions both involving measurements of binocular accommodation, monocular accommodation (closed loop) and phoria (vergence open loop) over a period of 20 minutes. Binocular accommodation was measured when both eyes fixated the target but only measures from right eye were recorded. For measurement of monocular accommodation, the left eye was occluded and accommodation was measured in the right eye.

One session was performed with the participants wearing habitual corrective lenses (referred to as *"no lens condition"* for the rest of the thesis) and the other involved measurements with +2D lenses (referred to as *"lens condition"* for the rest of the thesis) added over the habitual correction in a trial frame. The trial frame was adjusted for the participants near pupillary distance so as to reduce the prismatic effect that may be caused due to decentration of the plus lenses. The order of testing was randomized and the 2 study sessions were performed on different days (separated at least by 24hrs) to prevent contamination of results due to adaptation effects of either session.

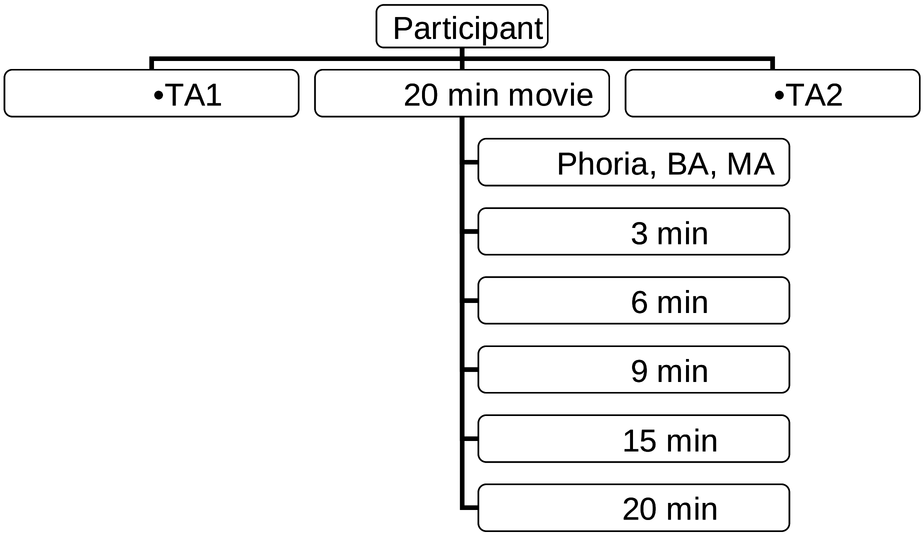


Figure 11: Schematic illustrating the experimental procedure performed on both the study sessions.

Measures of phoria, binocular accommodation (BA) and monocular accommodation (MA) were obtained at frequent intervals with and without +2D addition lenses. Pre-task tonic accommodation (TA1) and post-task TA (TA2) were also measured.

A schematic of the experimental procedure is shown in Figure 11. All participants were comfortably seated with their head in a chin/ head rest assembly to maintain constant testing distance throughout the study. The light level in the testing room was reduced to approximately 10 lux to obtain sufficiently large pupil sizes (greater than 4mm as recommended by the manufacturer of PowerRefractor). Prior to the start of the study, all participants were dark adapted for 3 minutes (Wolf et al., 1987) to avoid any accommodative or vergence adaptation that occurred during previous near work. Immediately after dark adaptation, pre-task tonic accommodation (TA1) was measured by instructing participants to fixate monocularly (left eye occluded) at a low spatial frequency (0.2 cpd) difference of Gaussian (DOG) target placed at a distance of 3.5 meters.

Baseline near phoria was then measured using the MTT and tangent scale as described in the earlier section. A flashing technique (similar to the method used by (Henson et al., 1980) was used to prevent voluntary fusion by occluding the image seen by the right eye (with Maddox) for approximately 10 sec. Heterophoria was determined from the average of three responses. The display of the LCD monitor was then changed to the colored picture for measurement of accommodation. Accommodation was recorded continuously for a period of 10sec (each) under both binocular and monocular viewing conditions using the monocular measurement mode of the PowerRefractor. Measurements were taken after confirming steady fixation at the target using the gaze control function displayed on the PowerRefractor interface. Responses were obtained for an additional 5 sec period if the participant did not maintain steady fixation (defined as deviation in gaze greater than 5 degrees) at the target. The areas of unsteady fixation were identified on the PowerRefractor interface as “flags” (keyboard inputs) and these regions were excluded during data analysis (appendix 3).

One complete cycle of measurement (measurement of phoria, binocular and monocular accommodation) took 1.05 ± 0.2 minutes. The display on the LCD monitor was then toggled to show the cartoon movie. A timer was set to beep after 3 minutes of near task and measures of phoria, binocular and monocular accommodation responses were repeated. The participant then continued to watch the movie, and subsequently measures of phoria, binocular and monocular accommodation was determined after 6, 9, 15 and 20 minutes of near task. Post-task tonic accommodation (TA2) was measured immediately after the 20 minutes near task with their habitual corrective lenses using the procedure similar to the pre-task TA assessment.

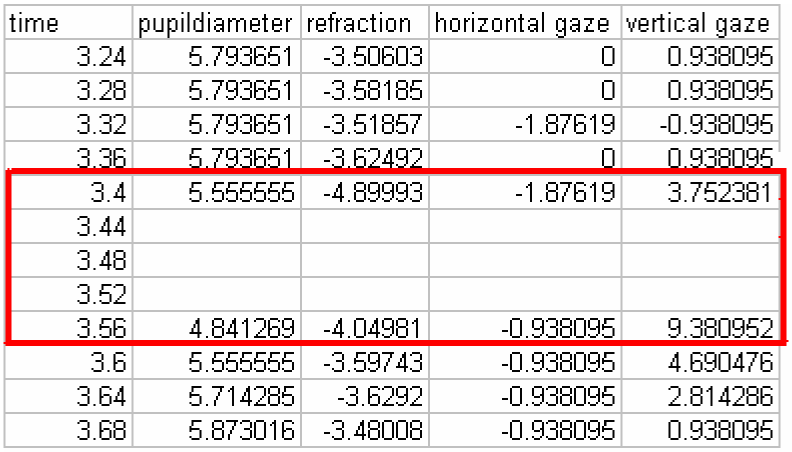
3.5 Data analysis

3.5.1 *Averaging of accommodation data from spread sheet*

Accommodative response at each time point was estimated by averaging the 250 data point's obtained over a 10 sec period (PowerRefractor provides 25 measures over a one second period - see Figure 5 PowerRefractor interface during measurement of accommodation). The measurements obtained using the PowerRefractor were exported to a spread sheet that provided information about the accommodation, pupil diameter and gaze positions. Each data point was accepted if the following criteria were met: The pupil size was above 4mm, the horizontal and vertical deviations in gaze were less than 5 degrees from the center of the camera, and the responses were free of blinks.

3.5.2 *Removal of Blink artifacts from the accommodative response*

Closer inspection of the continuously recorded data points showed a break in response accompanied by increased myopic refractions and reduction in pupil diameter every time a participant blinked during the measurement of accommodation (see Figure 12 and Figure 13 for example of spreadsheet data and graph illustrating the blink artifact). The myopic shift in refraction is speculated to be due to the reduction in pupillary diameter affecting the intensity gradient of the reflex (Allen et al., 2003)



time	pupildiameter	refraction	horizontal gaze	vertical gaze
3.24	5.793651	-3.50603	0	0.938095
3.28	5.793651	-3.58185	0	0.938095
3.32	5.793651	-3.51857	-1.87619	-0.938095
3.36	5.793651	-3.62492	0	0.938095
3.4	5.555555	-4.89993	-1.87619	3.752381
3.44				
3.48				
3.52				
3.56	4.841269	-4.04981	-0.938095	9.380952
3.6	5.555555	-3.59743	-0.938095	4.690476
3.64	5.714285	-3.6292	-0.938095	2.814286
3.68	5.873016	-3.48008	-0.938095	0.938095

Figure 12: Spreadsheet showing typical blink artifact response.

It can be seen from the above picture that during a blink, the PowerRefractor fails to measure responses for a brief period which is accompanied by a reduction in the pupillary diameter and an increase in myopic refraction.

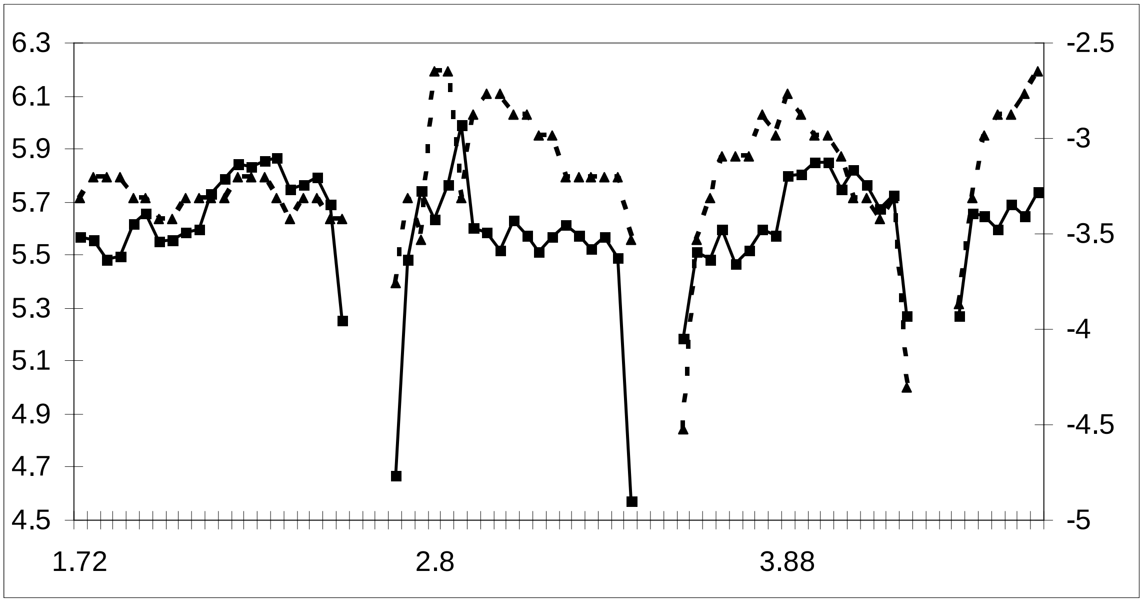


Figure 13: Graphical representation of a typical Blink artifact response.

Solid line indicates accommodative response and dotted line denotes pupil diameter. Blank responses can be seen to be accompanied with concurrent reduction in pupillary diameter and increase in myopic refraction every time a participant blinked.

In the current investigation, these erroneous values were manually removed by deleting one data point before and after the blank (total of 2 data points- see Figure 12). This led to a discarding of 2% of the data. A similar criterion for removal of blink artifacts has been used by previous investigators (Allen et al., 2003). Following removal of blink artifacts, the data points retained were averaged to obtain the accommodative response for a particular time point.

3.6 Exclusion of study participants

Upon averaging accommodative response, the data of four participants (two adults and two children) could not be considered for further analysis due to difficulty in obtaining sufficient data. Most of the data points (more than 50%) were lost due to a smaller pupillary diameter (less than 4mm). The PowerRefractor provides reliable responses only when the pupillary diameter is greater than 4mm (Choi et al., 2000) and thus manual removal of data points with small pupils led to very little data (ranged between 50-100 points only) for averaging. Additionally, the study was not performed in one adult participant (ID # 4) due to extremely small pupil size (less than 3.5mm) in which case, the PowerRefractor failed to record any measurements. Thus data from 8 emmetropic adults and 11 emmetropic children were included for statistical analysis.

3.7 Statistical analysis

In the current investigation, each participant had responses (binocular accommodation, monocular accommodation and phoria) taken over 6 different time points under two different test conditions (with and without near addition lenses). Repeated measures analyses of variance (RM-ANOVA) were performed to determine the main effect of lens condition and time on accommodation and phoria. In all cases, statistically significant main effects were further examined using Tukey Honestly significant differences (HSD) post-hoc tests to determine the precise time point that showed significant difference. Differences were considered statistically significant when the likelihood of type-I error was <0.05. Data analysis was performed using STATISTICA 6.0 (StatSoft, Inc, USA) and graphs were plotted using GraphPad Prism (GraphPad Software Inc, USA).

3.7.1 Exponential curve fitting

The reduction of exophoria was plotted as a function of time and an exponential function (Adaptation = magnitude of adaptation (1-exp (-rate constant*time) was fit to determine the rates and magnitudes of adaptation. Magnitude refers to the actual amount of reduction in exophoria upon saturation and is expressed in prism diopters (PD). Time constant refers to the time taken for 63% of total adaptation to occur and is expressed in minutes. In the current study, the rate of decay was calculated in terms of rate constant (from the exponential function) and time constant was estimated by obtaining an inverse of the rate constant. The curve fitting was conducted using GraphPad Prism (GraphPad Software Inc, USA)

4 RESULTS

4.1 Ocular motor parameters in emmetropic adult population

4.1.1 Accommodative response with and without near addition lenses

Figure 14 shows the accommodative measures obtained at a near testing distance of 33cm (Stimulus to accommodation = -3.00 D) during the no lens and the lens viewing conditions (with +2D lenses). All accommodative measures are expressed in terms of plane of focus (defined as the sum of lens power + accommodative response). Thus, for the no lens condition, the plane of focus measure equals the accommodative response and for the lens condition, the plane of focus measure is the sum of accommodative response and the 2D addition lenses. Additionally, it needs to be noted that throughout this thesis, the plane of focus measures are given a negative notation.

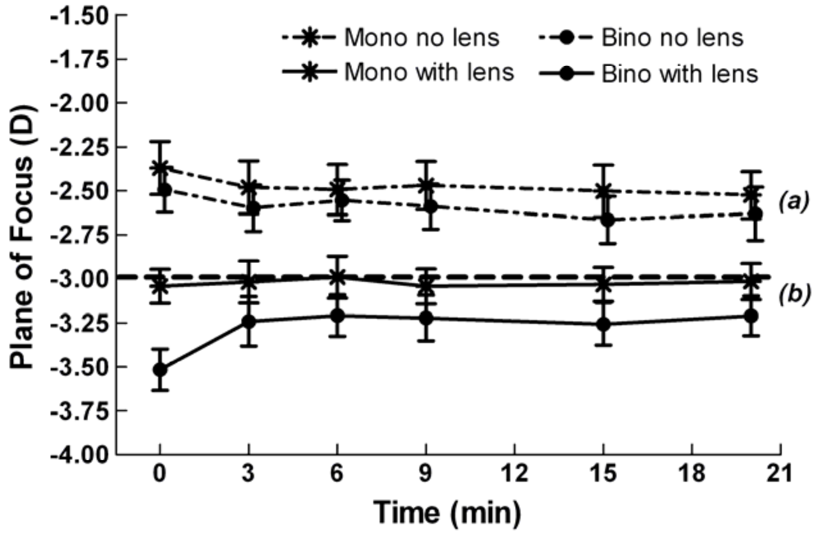


Figure 14: Plane of focus responses observed during no lens and lens viewing at 33cm

Dotted lines indicate plane of focus response measured during no lens condition and solid lines indicate plane of focus response measured with +2D addition lenses. Under both conditions, filled circles represent binocular responses and asterisks represent monocular responses. Error bars indicate mean ± SE

(a) No lens condition: Both binocular and monocular viewing conditions exhibit lags of accommodation that reduce over time with near work.

(b) Lens condition: Introduction of +2D lenses increased the plane of focus under both viewing conditions but the binocular focus alone showed a significant reduction after 3 minutes of near work.

4.1.1.1 No-lens condition

During the no lens condition (Figure 14 (a), dotted lines) the emmetropic adult sample, on an average, exhibited initial lags of accommodation of 0.51 ± 0.12D and 0.64 ± 0.15D under binocular and monocular viewing respectively. RM ANOVA showed a significant main effect of time with the higher lags of accommodation reducing significantly after the near task (Figure 14, Dotted lines; $F_{(5,\ 35)} = 6.84$; $P < 0.01$). The mean reduction in the binocular accommodative lag after 15 minutes of near work was 0.16 ± 0.15 D (post-Hoc tests: $P<0.05$) while the monocular lag reduced by 0.24 ± 0.13D over the same period. (Post-hoc tests: $P<0.05$). The binocular accommodative response was found to be consistently greater than the monocular response however, the viewing conditions did not show any significant main effect in the no lens condition (Main effect of viewing condition: RM ANOVA; F $_{(1, 7)}$ =4.26; P >0.05, Figure 14 and Table 4).

Time (mins)	**Differences between binocular and monocular focus (BF-MF) D**	
	No addition lens	**With +2D addition lens**
0	-0.12	-0.50*
3	-0.11	-0.25
6	-0.06	-0.24
9	-0.12	-0.20
15	-0.16	-0.25
20	-0.10	-0.22

Table 4: Differences between binocular and monocular focuses at various time points with and without +2D lenses

Negative response indicates greater accommodative response in binocular viewing condition. * Indicates statistical significance in accommodation response between the viewing conditions at P<0.05

4.1.1.2 Lens viewing condition

When participants viewed through the +2D near addition lenses a different pattern was observed. The demand for accommodation was reduced from 3D (target at 33cm under no-lens condition) to 1D with the introduction of +2D lenses and much of the plane of focus measure is being contributed by the +2D lenses.

Binocular addition of the +2D lenses increased the plane of focus significantly under both the monocular and binocular viewing conditions (Figure 14 (b), Solid lines; Overall significant main effect of lens- RM ANOVA, F $_{(1, 7)}$ = 9.25; P <0.05). The precise accommodative gains (defined in this context as change in plane of focus/lens power) immediately after insertion of +2D lenses were observed to be 0.51 and 0.32 under binocular and the monocular conditions respectively (see Figure 14). The averaged binocular plane of focus exceeded the demand (dotted line in Figure 14) by 0.51 ± 0.11 D at the baseline while the monocular measures were falling closer to the demand with the addition of +2D lenses. The mean differences between binocular and monocular focuses exhibited a significant main effect (viewing condition: RM ANOVA, $F_{(1,\ 7)} = 12.75$; $P < 0.01$) with the greatest difference observed at the reading onset (Difference: -0.5D post-hoc test $P<0.01$, Figure 14 and Table 4).

Two-way repeated measures ANOVA indicated a significant main effect of time on viewing conditions (Figure 14; RM ANOVA; $F_{(5,\ 35)} = 4.47$; $P<0.01$) with +2D addition lenses. However, further analysis using post-hoc Tukey HSD indicated significant reduction in the binocular focus alone. It was seen that the averaged binocular focus decreased significantly (magnitude of reduction: 0.24D; post-hoc $P<0.01$) after 3 minutes of near work (Figure 14, solid line and filled circle) with no further reduction observed beyond this time point. The monocular plane of focus measures remained stable with no significant changes observed throughout the 20 minute near fixation period (Figure 14, solid line with asterisk; post-hoc tests: $P<0.05$).

4.1.1.3 Tonic accommodation

Figure 15 illustrates the differences in open-loop accommodative responses (measured with the DOG target) before and after the 20 minutes near task, during the no lens and lens viewing conditions. Accommodative adaptation i.e. a statistically significant myopic shift (0.4 ± 0.08D, paired t–test: $P < 0.05$) in the tonic level was noted after sustained near work only in the no lens condition. Open loop accommodation measures with near addition lenses indicated no significant change (paired t–test; $P > 0.05$) in tonic accommodation following prolonged near fixation.

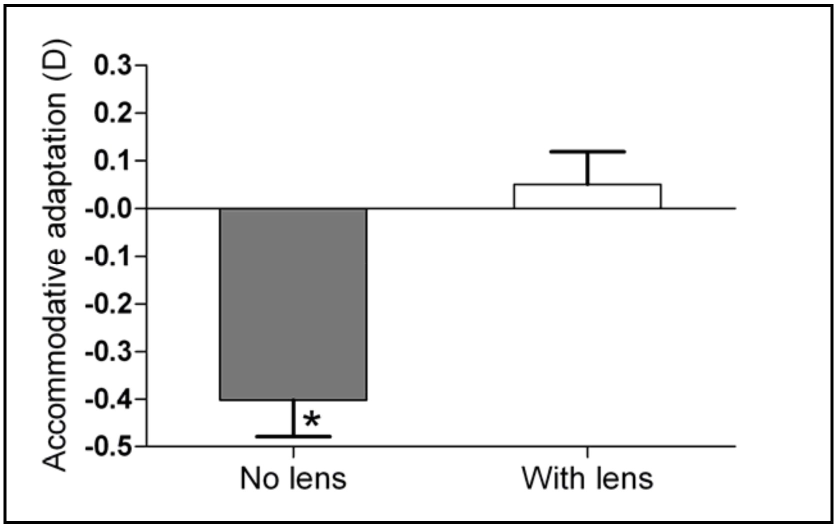


Figure 15: Accommodative adaptation with and without near addition lenses.

Accommodative adaptation was calculated by subtracting tonic accommodation (TA) measures before and after near task (Pre task TA – post task TA).

(a) No lens: TA showed a statistically significantly myopic shift following prolonged near task without addition lenses.

(b) With +2D: No significant post-task shift was observed in TA after 20 minutes of near fixation.

4.1.2 Phoria Response with and without near addition lenses

The average habitual near phoria of the adult population was observed to be -3.22 ± 0.48ΔD (with negative sign indicating exophoria). Figure 16 illustrates the change in near phoria during prolonged near work, with and without the near addition lenses. The phoria response under no lens condition was quite stable and did not show any statistically significant difference even after 20 minutes of near work (Figure 16, dotted line: RM ANOVA, post-hoc P>0.05)

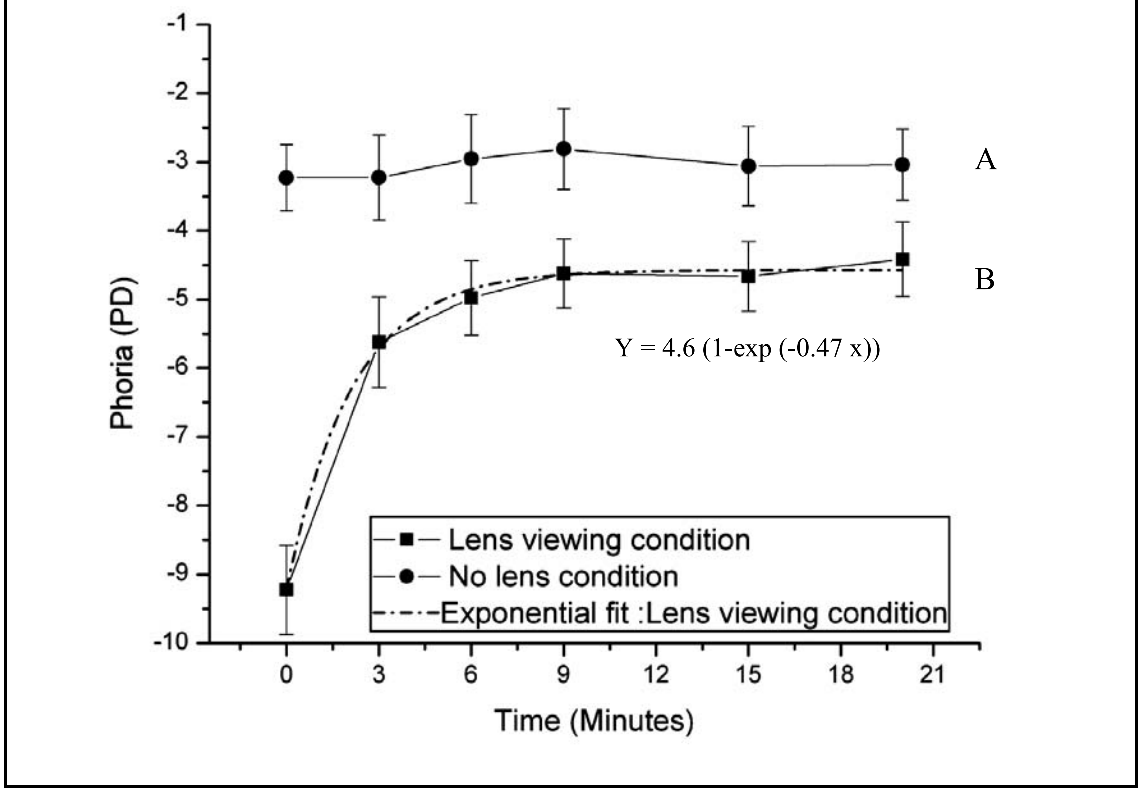


Figure 16: Phoria response with and without near addition lenses during 20 minutes of near fixation.

(A) No-lens condition: The phoria responses in the no-lens condition do not show any significant change over time (B) Lens-viewing condition: *Solid line* indicates the pattern of change in phoria over time with +2D lenses in front of both the eyes. Introduction of lenses increased the exophoria initially. Prolonged binocular viewing resulted in reduction of exophoria with greatest change occurring within the first 3 minutes of binocular fixation. *Dotted line* illustrates the exponential fit of changes in near phoria with addition lenses.

A different pattern of phoria responses was observed (Figure 16, solid line with circles) when the subjects viewed through the +2D lenses. There was a statistically significant main effect of lens condition on the phoria response (Figure 16, Solid line with squares; RM ANOVA; $F_{(1,\ 7)} = 12.72$: $P < 0.01$) with a significant increase in the mean near exophoria by 6 ± 0.56 ΔD at the baseline (Figure 16; post-hoc, $P<0.01$ compared to all other points). Sustained binocular fixation at the near task resulted in a reduction in the exophoria with a significant main effect of time (RM ANOVA; $F_{(5,\ 35)} = 48.12$: $P < 0.01$). Further analysis with post-hoc tests revealed a significant reduction in the mean exophoria following 3 minutes of binocular viewing at the near task (Figure 16, solid line; Magnitude of reduction: 3.6 ± 0.6 ΔD; post-hoc: $P<0.001$) This reduction occurred concomitantly with the reduction seen in binocular focus (See Figure 14). Upon continuation of binocular fixation at the near target, the mean exophoria was observed to reduce in an asymptotic manner. A further decline by a small magnitude (0.65 ± 0.5ΔD) was observed between 3 to 6 minutes of near viewing with little change taking place beyond 6 minutes of binocular viewing (post-hoc; $P>0.05$ after 6 minutes of near work). A statistically significant correlation was observed between the reduction in binocular focus and reduction of exophoria over prolonged binocular viewing at the near task (Pearson $r > 0.9$; $P<0.05$).

The reduction of exophoria over time was plotted using an exponential function to determine the magnitude and time constant of vergence adaptation (dotted line- Figure 16). The phoria responses fitted extremely well with an exponential function (Figure 16) having an R^2 value of 0.9. The magnitude of vergence adaptation was determined from the asymptote of the exponential function and was found to be 4.6 ± 0.21 ΔD for the emmetropic adult participants. The vergence 'adaptive gain', defined as the degree of phoria recovery divided by the initial change in phoria induced by the +2D lens was then calculated. The adaptive gain after 20 minutes of prolonged near viewing was found to be 0.76 (Magnitude of adaptation = 4.6ΔD / Initial induced phoria = 6ΔD) indicating that 76% of adaptation occurred after 20 minutes of binocular viewing. The time constant for the reduction in exophoria was observed to be 2.12 minutes signifying that 63% of total adaptation occurred within 2.12 minutes of binocular viewing.

4.2 Comparison between Adult and Children Data - Effect of Age

4.2.1 Accommodation and phoria responses in emmetropic children

The accommodative and phoria responses obtained from the emmetropic children (Figure 17 and Figure 18) were similar to that observed in the adult group (Figure 14 and Figure 16). Figure 17 and Figure 18 illustrate the accommodative and phoria response measured during no lens and lens viewing conditions in eleven emmetropic children. It can be seen from Figure 17 that child participants exhibited initial lags of accommodation (Binocular: 0.61 ± 0.06 D; Monocular: 0.9 ± 0.07 D) that were eliminated (under monocular viewing) and reversed (towards an over focus under binocular viewing condition) with the addition of +2D lenses (Main effect of lens condition - RM ANOVA, $F_{(1, 10)} = 38.62$: $P < 0.001$). An initial increase towards exophoria by 5.65 ± 0.76ΔD was also seen upon introduction of +2D lenses (Figure 18). A pattern of reduction of binocular focus (Main effect of time - RM ANOVA, $F_{(5,50)} = 5.56$: $P < 0.01$; post-hoc shows significant reduction in binocular focus alone after 3 mins, $P<0.05$) and concomitant reduction in exophoria after 3 minutes of binocular viewing was seen in the younger population (Main effect of time - RM ANOVA, $F_{(5,50)} = 43.34$: $P < 0.001$; post-hoc shows significant reduction in phoria with +2D lenses after 3mins , $P<0.001$) similar to that observed in adults (Figure 14 and Figure 16). Additionally, the reduction in exophoria was found to be significantly correlated with the reduction in binocular focus (Pearson $r > 0.9$, $P < 0.05$) indicating a strong association between the two variables.

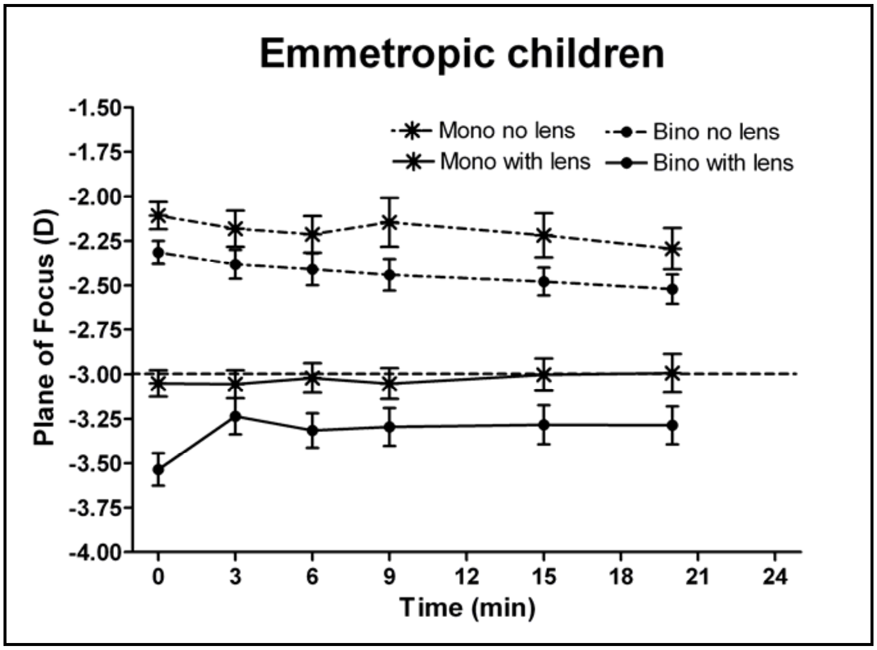


Figure 17: Mean plane of focus responses in emmetropic children during no lens and lens viewing conditions.

Dotted lines indicate plane of focus response without addition lens and solid lines illustrate plane of focus measures with +2D addition lenses. Under both conditions, filled circles represent binocular responses and asterisks represent monocular responses.

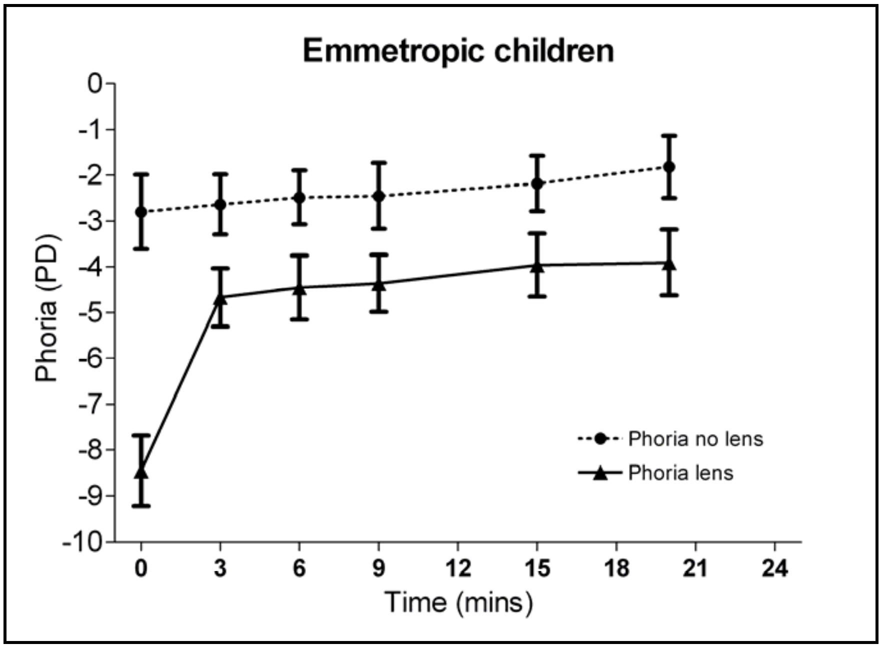


Figure 18: Phoria responses measured during no lens and lens viewing conditions in emmetropic children

Dotted line illustrates phoria response measured without near addition lenses and solid line represents response measured with +2D near addition lenses.

Figure 19 compares the adaptation curves (exponential function) of the two age groups. It can be seen that both the groups showed similar trend for reduction in exophoria with the greatest reduction occurring within the first 3 minutes of binocular viewing. Comparison of the magnitude of adaptation (saturation point in Figure 19) showed no significant difference between the two groups (Adults: 4.65 ΔD; Children: 4.51 ΔD; $F_{(1, 8)} = 1.95$, $P > 0.05$). The time constants for reduction in exophoria also showed statistically insignificant differences between the two groups (Adults: 2.12 minutes: Children: 1.53 minutes $F_{(1, 8)} = 1.95$, $P > 0.05$).

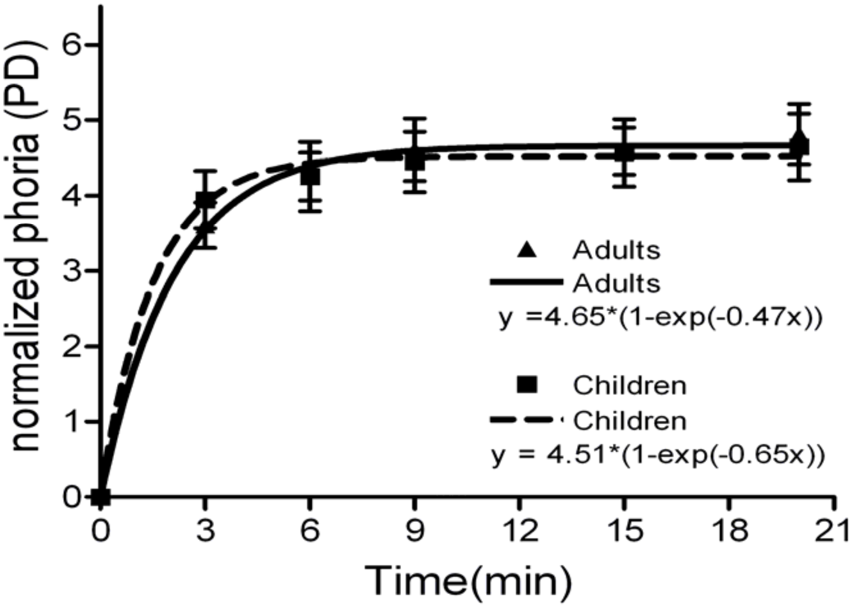


Figure 19: Comparison of phoria adaptation curves between emmetropic adults and children

The normalized phoria (baseline phoria with +2D lenses subtracted from all subsequent measures) illustrates similar pattern of responses between the two groups. Both the magnitude of adaptation as well as the time constant was not found to be significantly different between the two groups.

Moreover, the AV/A ratio that determines the amount of exophoria induced by the addition of +2D lenses did not show any statistically significant difference between either groups (Unpaired t-test: t= 0.53, P >0.05; Figure 20).

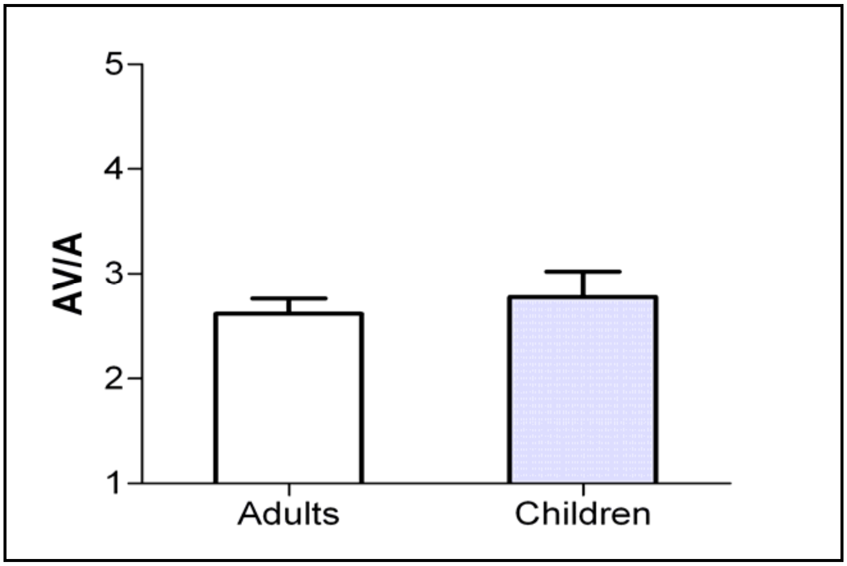


Figure 20: Comparison of AV/A ratio in the two age groups.

The mean stimulus AV/A ratios estimated using Gradient AV/A method were not found to be significantly different between the two groups.

4.3 Comparison of different AV/A ratios and its effect on vergence adaptation

For this section of analysis, all participants (emmetropic adults and children) were grouped together due to the insignificant effect of age on adaptation to lens induced heterophoria. The stimulus and response AV/A ratio of all participants (N = 19) were determined using the Gradient AV/A method (Borish, 1975). Two different stimulus AV/A ratios were obtained and analyzed. The first stimulus AV/A (St AV/A +1) measure was obtained by changing the accommodative stimulus by 1D (the conventional testing method and was performed as a part of the screening protocol). The second stimulus AV/A ratio (St AV/A +2) was derived from the experimental results wherein the accommodative stimulus was altered with +2D lenses. Under both conditions, only the relative change in accommodative vergence was measured and the change in accommodation was assumed (Technique for measuring stimulus AV/A ratio clinically (Borish, 1975). A third measure, the response AV/A ratios (R AV/A) were also derived from the experimental results (Accommodative and phoria measures with +2D lenses). For this ratio, the changes in accommodation was not assumed but were calculated by determining the difference in monocular focus with and without +2D lenses. Thus, three AV/A ratios, two calculated from the experimental condition and one obtained on a separate occasion (screening visit) were compared. Figure 21 shows the comparisons between the three conditions. One way RM- ANOVA indicated an overall significant effect of the testing method on the AV/A ratio (Figure 21; RM-ANOVA $F_{(2, 34)} = 1.95$, $P < 0.05$). Further analysis with the post-hoc test reveal no significant differences between both the stimulus AV/A ratios (St AV/A+1 and St AV/A+2) indicating linearity of the

AV/A ratio in the tested range. The response AV/A ratio was found to be significantly greater than both the stimulus conditions (Post-Hoc; P<0.05) However, the association between the stimulus and response AV/A ratios was found to be strong with a statistically significant positive correlation (Pearson r = 0.81; P<0.01; Figure 22) indicating that majority of participants who exhibited a higher St AV/A ratio also exhibited a higher R AV/A ratio.

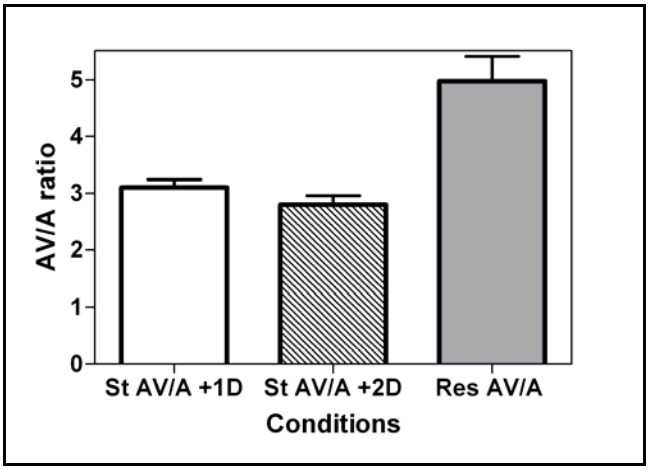


Figure 21: Comparison between three AV/A conditions.

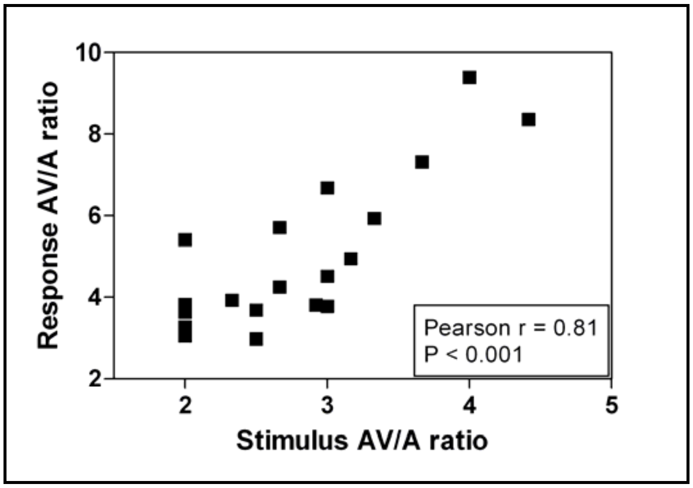


Figure 22 : Correlation between stimulus and response AV/A ratios.

4.3.1 The effect on different Stimulus and Response AV/A ratios on Vergence adaptation

The mean stimulus and response AV/A ratios of the study population are shown in Figure 21. The range of stimulus AV/A ratios for all the study participants (11 children and 8 adults) was observed to be from 2 ΔD/D to 4.5 ΔD/D and their response AV/A ratio’s ranged between 2.9 ΔD/D and 9.4 ΔD/D. Table 5 provides information about the stimulus and response AV/A ratios of the entire study group. The response AV/A ratios were categorized into two groups: Low response AV/A group (R AV/A group) with ratios ranging from 2.9 – 4 ΔD/D; and the High R AV/A with ratios between 4 Δ/D and 9.4 ΔD/D. The stimulus AV/A (St-AV/A group) were also divided into two groups but the division was narrow due to the limited range of St-AV/A ratios available. The low St-AV/A group comprised of participant’s with ratios ranging between 2 and 2.7 ΔD/D and the high St-AV/A group included ratios ranging between 2.9 - 4.5 ΔD/D. As seen from Table 5, majority of the study participants (15/19) were classified into the same category of AV/A ratio (i.e. the participants showed a low R-AV/A ratio when they had low stimulus AV/A ratio). Only 4/19 participants did not fall appropriately in the respective cut-off category (identified as asterisks in Table 5). However, in most of these misclassified cases the respective category was missed by a small magnitude (for e.g. ID 18 had a stimulus AV/A ratio of 2.9ΔD/D and a response AV/A ratio of 3.8 ΔD/D).

Figure 23 (A) - (D) demonstrates the reduction of exophoria and their exponential functions for the two ranges (Low and High) using the two testing methods (Stimulus and Response AV/A). It can be seen from Figure 23 (A) - (D) that the stimulus and response

AV/A ratios produce a similar pattern of reduction in exophoria with the greatest, statistically significant reduction occurring within the first 3 minutes of binocular viewing (High St-AVA: 3.98 ΔD; High R-AV/A: 4 ΔD; Low St-AV/A: 3.47 ΔD; Low R-AV/A – 3.3 ΔD). The "vergence adaptive gain" (recovery of exophoria/initial induced phoria) was calculated to be 0.76 (St-AV/A) and 0.73 (R-AV/A) for the low AV/A group and 0.58 (St-AV/A) and 0.61 (R-AV/A) for the high AV/A group after 3 minutes of near task. After 20 minutes of binocular viewing, the groups with smaller induced phoria showed close to complete adaptation (gain 0.92 for St-AV/A and 0.94 for R-AV/A) compared to the groups with greater induced phoria. The high AV/A groups exhibited incomplete adaptation with a gain of 0.76 and 0.75 under St-AV/A and R-AV/A testing conditions respectively. The magnitudes of adaptation (determined by the saturation values - asymptote of the exponential fit) was found to be statistically significant ($F_{(3, 16)} = 10.06$, $P < 0.01$) between the two groups under both the testing conditions. The greatest amount of adaptation was observed in the high AV/A groups {(Stimulus and Response) (Figure 23 C and D; Magnitude of adaptation: Low St-AV/A = 4.12 ΔD; Low R-AV/A= 4.25DΔ; High St-AV/A = 4.88 ΔD; High R-AV/A = 4.65ΔD)}. The time constants, however did not show statistically significant differences between any of the tested groups (Low St-AV/A = 1.78 min; Low R-AV/A= 1.72 mins; High St AV/A = 1.88min; High R-AV/A = 1.92 mins $F_{(3, 16)} = 0.09$, $P > 0.05$).

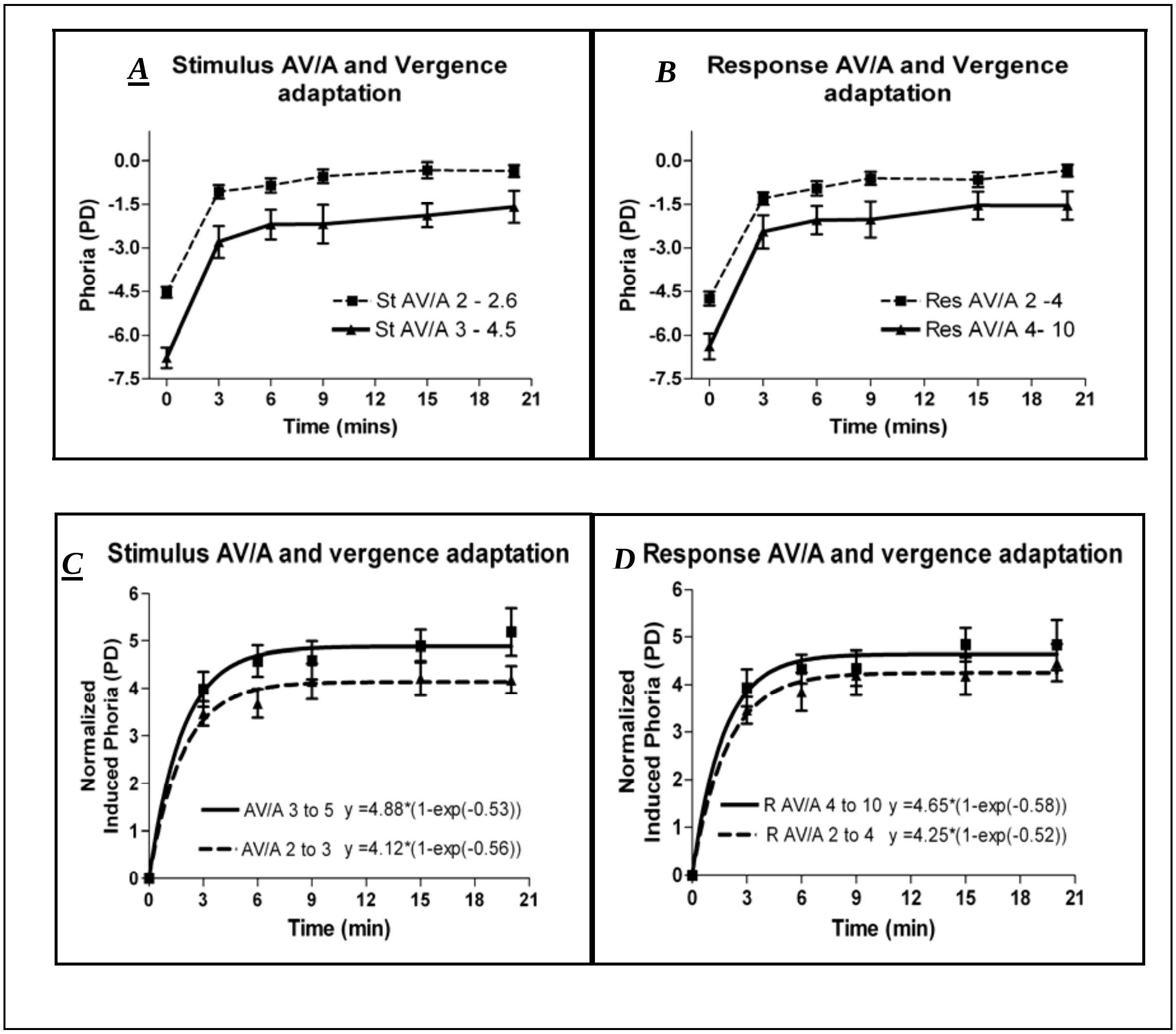


Figure 23: AV/A ratios and phoria adaptation using two testing methods

(A) and (B) : Demonstrates the changes in phoria response as a function of their starting points (AV/A ratios) determined using both the stimulus (A) as well as response techniques (B).

(C) and (D): Exponential curve fit of the adaptation curves for the stimulus (C) and response AV/A (D) ratios. The ordinate of the graph illustrates the phoria response normalized to their baseline induced phoria.

The correlation between vergence adaptation and AV/A was evaluated by individually assessing the amount of phoria adapted by each study participant after the near task and comparing the responses with their AV/A ratios. The magnitude of adaptation (asymptote) was estimated by fitting an exponential function to the phoria response obtained from each participant. Table 5 shows the stimulus AV/A, response AV/A and the asymptotes obtained for all study participants. The individual magnitude of adaptation was then plotted as a function of their respective stimulus (Figure 24 - A) and response AV/A ratios (Figure 24 – B) to establish the relationship between the AV/A ratio and adaptation. Correlation analysis indicated a moderate yet significant relation between the two variables under the stimulus as well as response AV/A conditions (St-AV/A ratio Pearson r=0.52; P=0.02; Response AV/A ratio: Pearson r =0. 48; P = 0.02).

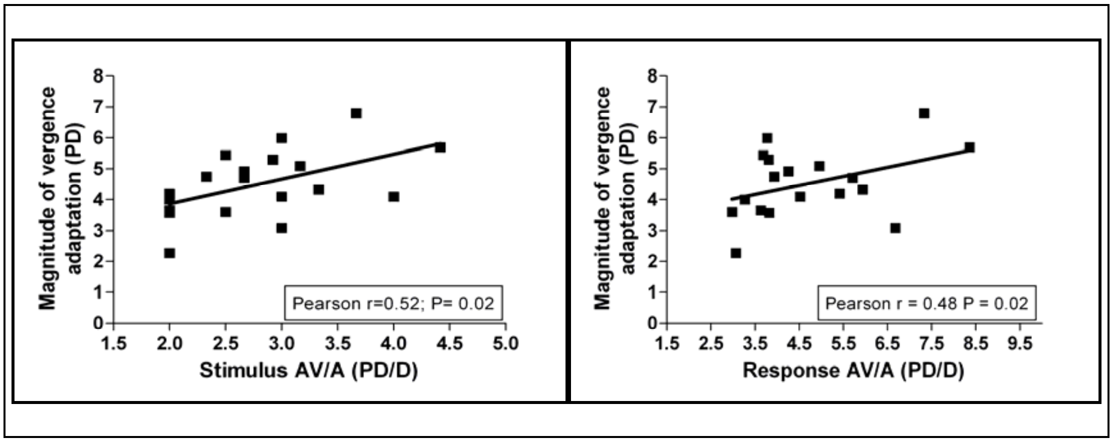


Figure 24 : Plot comparing the relation between AV/A and magnitude of phoria adaptation.

(A): Comparison between stimulus AV/A and magnitude of adaptation

(B) Comparison between response AV/A and magnitude of adaptation

ID Number	St AV/A ratio (Δ/D)	Response AV/A ratio(Δ/D)	Magnitude of adaptation ΔD (Asymptote)
1	2	3.26	4
2	2	3.82	3.57
3	2	5.41	4.2
4	2	3.62	3.65
5*	2.66	4.25	4.92
6*	2.66	5.71	4.71
7	2.5	3.68	5.45
8	2.33	3.93	4.75
9	2	3.06	2.28
10	2.5	2.98	3.6
11	4.41	8.36	5.7
12	4	9.40	4.1
13	3.66	7.33	6.8
14	3	4.52	4.1
15	3.33	5.93	4.33
16*	3	3.77	6
17	3.165	4.95	5.1
18*	2.92	3.80	5.3
19	3	6.68	3.1

Table 5 : Magnitude of adaptation (determined from the asymptote of exponential fit) for each study participant.

Asterisks identify those participants who do not maintain the cut-off category of AV/A ratios

Accommodative responses with +2D lenses showed a trend similar to that observed in previous sections (Figure 14 and Figure 17 with significant reduction in binocular focus alone concomitant with the reduction in exophoria. Statistically significant correlation (r >0.9; P<0.05) was observed between the reduction in exophoria and binocular focus in both the AV/A groups. However, the magnitude of reduction in binocular focus (magnitude of vergence accommodation) did not show any significant difference between the two groups (Figure 25; Low AV/A: 0.26D; High AV/A: 0.32D; P>0.05).

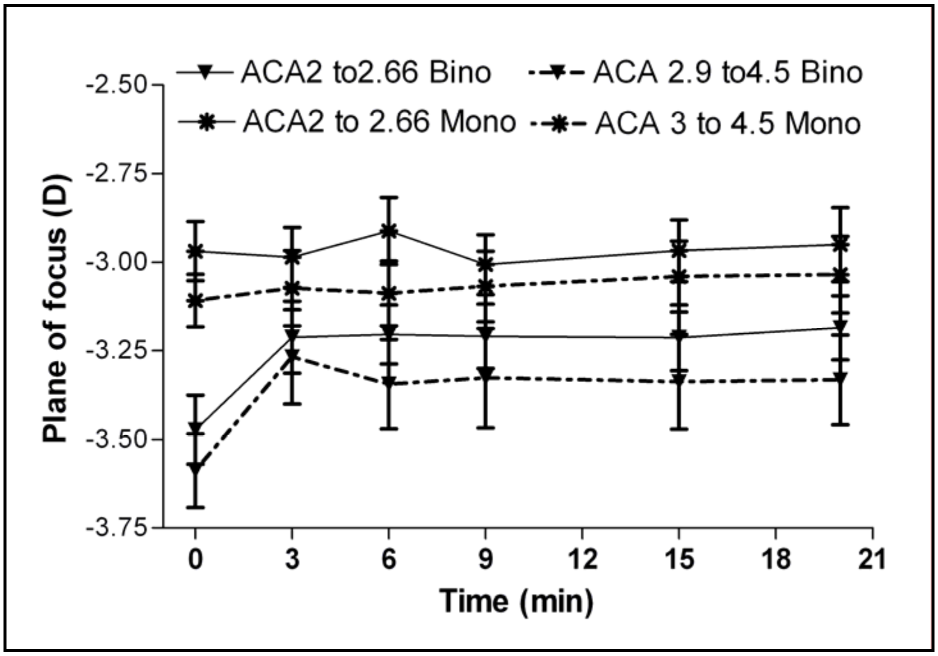


Figure 25: Plane of focus response in the two groups with and without addition lenses.

Dotted lines indicate accommodative response without addition lens and solid lines illustrate plane of focus measures with +2D addition lenses. Under both conditions, filled squares represent binocular responses and asterisks represent monocular responses.

5 DISCUSSION

This is the first investigation which provides information on the complete sequence of binocular accommodation, monocular accommodation and vergence responses to the addition of plus lenses during a sustained period of near viewing. The objective of prescribing near addition lenses to pre-presbyopic individuals has been to control accommodation and thereby the accommodative vergence (Birnbaum, 1979; Birnbaum, 1985; Birnbaum, 1993; Goss, 1986; Greenspan, 1981; Gruning, 1985). However, previous studies have only evaluated the effect of these lenses independently on the accommodation system (Easwaran, 2005; Rosenfield & Carrel., 2001; Seidemann & Schaeffel., 2003; Shapiro et al., 2005) or vergence system (Maddox & Edin., 1893; North & Henson., 1985; Schor, 1979b), either immediately after introduction of plus lenses (Rosenfield & Carrel., 2001; Seidemann & Schaeffel., 2003) or with sustained near work (North & Henson., 1985). But, until now no study has concomitantly measured the effect of these lenses on both the motor systems over a period of sustained near task. It is well known that under binocular viewing conditions, accommodation and vergence systems are mutually interlinked through AV and VA cross links where optically stimulated accommodation evokes convergence (Alpern et al., 1959; Maddox & Edin., 1893) and vice-versa for disparity stimulated vergence (Fincham & Walton., 1957). Additionally, while it is known that pre-presbyopic individuals demonstrate an ability to adapt to the exophoria induced by plus lenses (North & Henson., 1985), there is a paucity of information on how vergence adaptation influences the overall accommodative response during prolonged near activity. Thus, this investigation was aimed to comprehensively study the time course of changes to the accommodation and vergence system as the oculomotor system adapts to the near addition lenses. The results of this investigation facilitates a clear understanding of mechanism outlining the changes to both the ocular motor system with findings consistent with the current models of accommodation and vergence (Figure 2) (Hung & Semmlow., 1980; Schor & Kotulak, 1986; Schor, 1992).

5.1 Mechanism outlining changes to the accommodation and vergence systems when viewing through near addition lenses

5.1.1 Initial response with +2D lenses: Increase in exophoria and convergence accommodation

The introduction of +2D near addition lenses resulted in three important changes to the ocular motor system at the reading onset. The changes include: An increase in both the binocular and monocular plane of focus (it should be noted accommodation has reduced compared to the no lens condition and much of the plane of focus is contributed by +2D lenses), a significant increase in exophoria upon opening the loop of vergence and significantly greater differences between the binocular and the monocular focuses at the reading onset.

The increased plane of focus observed under binocular and monocular viewing conditions was similar to the results observed in previous studies (Easwaran, 2005; Rosenfield & Carrel., 2001; Seidemann & Schaeffel., 2003; Shapiro et al., 2005) A comparative summary of the results of the current study with previous studies are provided in Table 6. It is evident from Table 6 that the lags of accommodation observed under the no lens condition reduces with the addition of low powered plus lenses. In addition to the reduction of lag of accommodation seen under monocular viewing condition (Table 6) binocular measures showed that these lenses also resulted in a response that exceeded the near target. However, as noted earlier, accommodative response itself had declined with the addition of +2D lenses. The resulting increase in exophoria is due to the relaxation of accommodation vergence following the reduced accommodation and is in accordance with the participant's AV/A ratio. This finding was confirmed by similarity between the AV/A ratio's obtained on two separate occasions.

The mean exophoria (6 ± 0.56 ΔD) induced due to +2D lenses are consistent with findings observed in the literature (Maddox & Edin., 1893; North & Henson., 1985; Schor, 1979b). However, since the exophoria was induced in accordance with the participant's AV/A ratio, individual differences would be expected, depending upon the range of AV/A ratio's found in the study. The mean stimulus-AV/A ratio (3 ± 0.16 ΔD/D) and response AV/A ratio (4.97 ± 0.40 ΔD/D) were observed to be within the normal range and are similar to the existing literature (Alpern et al., 1959; Bruce et al., 1995; Manas, 1958; Manas, 1958; Ogle & Martens., 1957; Rosenfield et al., 1995). The majority of the study population had response AV/A ratios closer to the normal range however three participants exhibited AV/A ratios as high as 8–9 ΔD/D. This could partly be explained by the incomplete relaxation of accommodation (lower denominator in the AV/A ratio) observed in these individuals.

Under binocular viewing condition, the lens induced exophoria would trigger the fusional vergence system to produce an increase in reflex convergence through negative feedback mechanism (Figure 2). The increase in fusional convergence, in turn results in an immediate increase in binocular focus through the convergence accommodation crosslink (Schor & Kotulak., 1986; Schor, 1992) (VA, see Figure 2). This increase in VA explains the over driven binocular focus and the greater difference observed between the binocular focus and monocular focus at the onset of lens addition. Similar differences between the viewing conditions were also observed in previous studies (Seidemann & Schaeffel., 2003; Shapiro et al., 2005) (see Table 6)

Study	**STA (D)**	**AE without add**		**AE with +1 D**		**AE with +2D add**	
		B	**M**	**B**	**M**	**B**	**M**
Current study	3D	-0.51 ± 0.36D	-0.64 ± 0.42D	Not done	Not done	0.51 ± 0.33D	0.01 ± 0.27D
Seidemann (2003)	3D	-0.12 ± 0.45D	-0.29 ± 0.35D	0.25 ± 0.44D	0.02 ± 0.32D	0.77 ± 0.46D	0.39 ± 0.26D
Shapiro (2005)	3D	-0.03 ± 0.3D	-0.08 ± 0.2D	Not done	Not done	0.90 ± 0.3D	0.65 ± 0.3D
Easwaran (2005)	3D	-0.55 ± 0.14	Not done	0.05± 0.08	Not done	0.64 ± 0.06	Not done

Table 6: Comparison of accommodative error observed in different studies with and without plus lenses under both binocular and monocular viewing conditions.

Plus sign indicates lead of accommodation and minus sign indicates lag of accommodation.

5.1.2 Vergence adaptation and reduction of vergence accommodation

A significant reduction in exophoria was found within 3 minutes of binocular fixation at a near task. This reduction in exophoria can be attributed to *vergence adaptation*. (Ogle, 1950; Schor, 1979a) Adaptation of the vergence system has been reported to occur in response to a prolonged output of reflex vergence (Schor, 1979a; 1979b). As proposed by Schor (1979a), it is presumed that in the current experimental results the fast component mediated the initial increase in fusional convergence in response to the increased exophoria produced by plus lenses. The fast fusional vergence, with prolonged binocular viewing provided the input to the slow fusional component. The slow component due to its long decay time constant (Ellerbrock, 1950; Ogle, 1950; Schor, 1979a) resulted in a reduction in exophoria which in turn decreases the input to reflex convergence through negative feedback mechanism (see Figure 3).

The reduction in reflex convergence then decreases the convergence accommodation. As a result, the binocular focus (that exceeded the near target initially) reduced and approached a response closer to the monocular measures. This finding is consistent with Schor’s model (Schor & Kotulak., 1986; Schor, 1992) which suggests reduction of cross-link interactions upon adaptation of the respective ocular motor system and the empirical findings reported by Jiang (1996) (adaptation of the accommodation would reduce the fast component and result in a reduced AV).

Additionally, the reduction in exophoria that was seen following prolonged binocular viewing (defined as vergence adaptation) could have occurred if there was a reduction in the AV gain as a result of adaptation of accommodation. However, the findings of the study clearly refute this possibility for two reasons: (1) the open-loop tonic accommodation measures were not different before and after the near task indicating the absence of accommodative adaptation, and (2) the monocular plane of focus measures with +2D lenses was steady over time suggesting that the accommodative convergence cross link was not significantly altered during the process. Thus, vergence adaptation can be considered as a mechanism that functioned to both reduce reflex vergence and to provide a closer match between the binocular and monocular focuses with near addition lenses.

The results of the current investigation agree with empirical studies of adaptation to plus lenses. North and Henson (1985) reported a similar reduction in phoria (46.5%) within 3.5 minutes of near fixation with further gradual reduction (70%) following 35 minutes of binocular viewing. The average magnitudes of adaptation in the current study were observed to be 60% and 76% after 3 and 20 minutes of binocular fixation respectively. The slight variation in the mean findings is explainable on the basis of differences in the accommodative-vergence components.

5.1.3 AV/A and phoria adaptation

Adaptation to lens induced heterophoria differs from prism induced heterophoria, in that the magnitude of the adapting stimulus in the former case depends on individuals AV/A ratios unlike the similar disparities created by the introduction of a prism. In the current investigation, the effect of AV/A ratio on vergence adaptation was analyzed using two testing methods (Stimulus and response AV/A ratios) each consisting of two study groups (Low AV/A and High AV/A). Though the mean response AV/A ratio was significantly greater then the stimulus AV/A ratio, the pattern of reduction of exophoria along with the time constant and magnitude of adaptation was similar between the two testing methods.

Individuals with higher AV/A ratio's, on an average, showed significantly greater magnitudes of vergence adaptation compared to those with lower ratios under both testing conditions. This is best explained by considering that those individuals with higher AV/A ratios tend to have greater amounts of induced exophoria which in turn would result in greater reflex convergence and thus greater amounts of tonic adaptation (Schor 1979a). Similar results towards greater magnitudes of adaptation in individuals with higher induced phoria (Magnitude of adaptation after 30 minutes of binocular viewing: Low St- AV/A 3.8 ΔD (N=1) and High St- AV/A: 5ΔD (N=3); Values calculated from graphical results) were observed by North and Henson (1985). The association of adaptation with AV/A ratio (both stimulus and response) showed moderate yet significant positive correlation (r = 0.5) indicating that greater magnitude of adaptation occurred in individuals with higher AV/A ratio (both stimulus and response). Though the majority of the study participants with higher AV/A ratio showed greater adaptation, some individual differences did exist. For example, the response AV/A of ID

19 (Table 5) was 6.7ΔD:1D; however, he exhibited only 3.1 ΔD of adaptation. Excluding, this participant's data from the analysis increased the correlation to 0.7 ($P<0.001$).

In addition to the differences in magnitude, the current study also observed differences in completeness of adaptation between the two AV/A groups. Adaptation to lens induced heterophoria was found to be incomplete in individuals with higher AV/A ratios compared to those with lower ratios. Table 7 provides a comparison of the degree of adaptation in terms of adaptive gain (change in phoria/ induced initial phoria) as a function of St AV/A ratio in two studies (current study and North and Henson study (1985)) at two different time points.

Investigator	**Adaptive gain (Change in phoria/Induced phoria)**			
	Low St-AV/A (2-2.6ΔD/D)		**High St-AV/A(2.9-5ΔD/D)**	
	3 – 3.5 min	**After 20 min**	**3 – 3.5 min**	**After 20 min**
Current study	0.76 (N =10)	0.92 (N = 10)	0.58 (N = 9)	0.76 (N =9)
North and Henson	0.55 (N = 1)	0.86 (N =1)	0.43 (N = 3)	0.64 (N = 3)

Table 7: Comparison of adaptive gain as a function of AV/A ratio in two studies

The above table illustrates the strong agreement between the two studies in a finding that suggests greater yet incomplete adaptation in individuals with higher AV/A ratios. The adaptive gain in the group with higher AV/A ratio after 20 minutes of binocular viewing was similar to the initial gain (after 3 min) observed in the lower AV/A group. A closer look at Figure 23 (a) demonstrates gradual reduction of exophoria in the higher AV/A group even after 9 minutes of binocular viewing (time point where saturation occurred in the individuals with lower AV/A) suggesting that this group might come closer to their baseline if the binocular fixation time was prolonged. However, the investigation by North and Henson (1985) did not show completeness in adaptation even after 60 minutes of binocular viewing in three individuals with high AV/A. Moreover, it is important to note that the actual magnitude required for adaptation to be complete in the high AV/A group is only 1.6ΔD which is less than the repeatability coefficient of the measurement technique (appendix 2). Whether the adaptation response would achieve completeness with extended binocular viewing needs further investigation in a larger sample with greater range of ratios.

5.2 Effect of age on oculomotor parameters with near addition lens

This study is the first to analyze vergence adaptation to ophthalmic lenses in both adults and children. Comparative analysis based on age is necessary because near addition lenses are commonly prescribed to both pre-presbyopic adults and children to treat convergence excess (Jacob et al., 1980; von Noorden et al., 1978), for alleviating near point visual stress (Gruning, 1985) and to attenuate myopia progression (Greenspan, 1981; Grosvenor et al., 1987; Gwiazda et al., 2003). Many researchers have found AV/A ratio to be higher in myopic children compared to their emmetropic counterparts (Goss, 1991; Gwiazda et al., 2005), which might result in decreased vergence adaptive ability in these children. Therefore, before investigating vergence adaptation in an entity like myopia with various differences in ocular motor parameters, it becomes necessary to evaluate the more basic question of age. Accordingly we enrolled children without significant myopic refraction and compared their responses with emmetropic adults to tease out the effect of age. Studies investigating vergence adaptation with age have yielded conflicting results.

Wong et al (2001) compared vergence adaptation to a prolonged near task (reading at a distance of 15 cm for 5 minutes) in children (N=18; mean age = 9.8 years) and young adults (N=18; mean age 25.8 years) and concluded that adaptation was significantly greater in children compared to adults. However, they did not measure the accommodative response in either group and the differences could reflect changes to AV cross link. Additionally, they have not mentioned the refractive status of the study groups which have been reported to affect both accommodation and vergence responses (Gwiazda et al., 1996).

Owens et al (1991) measured both accommodative and vergence changes in 18 young adults and 20 children after a 20 minute near task at a distance of 16.5 cm. These authors did not find any significant task induced adaptation in either of the ocular motor systems for either study group. This report was an abstract from a conference presentation and to date no detailed report is available.

The results of the current investigation did not show any significant effect of age on vergence adaptation to +2D lenses. Neither the rate nor the magnitude of adaptation was found to be significantly different among the two study groups. The important factors that influence vergence adaptation are magnitude and duration of the adapting stimulus (Ellerbrock, 1950; Rosenfield, 1997). In case of lens induced heterophorias, the source for disparity and thus vergence adaptation would depend on the individual's AV/A ratio. This investigation did not find any significant differences in AV/A ratios between the two age groups. This would mean that the stimulus for vergence adaptation would also be similar for both the age groups. This similarity in vergence stimulus would provide equal inputs to the fast fusional components of both study groups resulting in insignificant differences in tonic adaptation (Schor, 1979a). The duration of test stimulus (experimental protocol) was also similar for both the age groups, thus ruling out any further chances for differences in adaptation. Thus, based on the study findings, we conclude that age does not seem to have a significant effect on vergence adaptation to near addition lenses within the range tested in the current investigation.

6 CONCLUSIONS AND FUTURE DIRECTIONS

The current investigation on pre-presbyopic adults and children extends the understanding of the binocular response to near lens additions during sustained periods of near fixation. In summary the key findings of this study are:

1. Introduction of near addition lenses initiated an increase in convergence and convergence driven accommodation comparable to the reports in literature.
2. Phoria adaptation occurred after 3 minutes of binocular viewing thus reducing convergence and convergence driven accommodation.
3. The magnitude and completeness of phoria adaptation were seen to depend on an individuals AV/A ratio with greater magnitude and incomplete adaptation observed in participants with higher AV/A ratios.
4. Age, within the limits of the study did not appear to influence phoria adaptation with near addition lenses.

Thus, the results of this investigation, consistent with both empirical findings and the models of the vergence and accommodation, underscore the need for and presence of robust vergence adaptation. The presence of rapid adaptive ability to lens induced exophoria can be considered as a mechanism that facilitates reduction of both vergence and accommodative errors over prolonged near viewing periods. This study also shows incomplete phoria adaptation in individuals with higher AV/A ratios. However, it would be worth evaluating the differences in adaptive ability to lens induced phoria's in a group of subjects with broader AV/A ratios.

Previous research indicates that myopic children demonstrate higher AV/A ratios than emmetropes (Goss, 1991; Gwiazda et al., 1996; Gwiazda et al., 1999; Gwiazda et al., 2005). Furthermore Rosenfield & Gilmartin (1988a) suggest that myopes may have reduced vergence adaptation however this has not been consistently found (North et al., 1989). Studies have not looked at this question in progressing myopes which would be important since their accommodative and accommodative vergence behavior differs from stable myopes (Abbott et al., 1998; Goss, 1991; Goss & Wolter., 1999; Gwiazda et al., 1995a; Gwiazda et al., 1996). Progressive myopic children show an esophoric shift in near phoria and exhibit higher lags of accommodation compared to stable myopes and emmetropes (Abbott et al., 1998; Goss & Jackson., 1996; Goss & Walter., 1999; Gwiazda et al., 2005). Clinical trials conducted to evaluate the effect of addition lenses show the greatest treatment effect in children with near esophoria (Fulk et al., 2000; Goss, 1994) combined with higher lags of accommodation (Gwiazda et al., 2004). It is possible that the near addition lenses act to lessen the esophoria towards orthophoria thereby placing less demand upon reflex convergence and also eliminates their excessive lags of accommodation. Whether this can in part explain the higher success of near adds in esophoric children needs further investigation.

Children, unlike presbyopic adults, usually have full accommodative ability and could use the distance part of their glasses to see clearly for near-visual tasks. They do not gain clear vision with addition lenses as older adults to reinforce using the lens for near-visual tasks. Therefore it is essential to perform a careful examination of binocular adaptation when near addition lenses are being prescribed for pre-presbyopic individuals.

APPENDICES

Appendix 1: Comparison of picture target and high-contrast text for measuring the accommodation response

Purpose

The current investigation used an interesting cartoon movie as a near target for maintaining the participant's attention for 20 minutes. A near colored picture target, similar to the movie was used for measuring accommodation during frequent intervals. The purpose of this study was to compare the accommodation response of the colored picture with that of a high contrast text placed at a near viewing distance of 33cms.

Description of targets

The high contrast (black on white – 92% contrast) target consisted of numbers (2.33 mm high) with a background luminance of 35 cd/m^2. The picture (Figure A1) had lots of information for the viewer but the attention of participants was directed towards "Mickey and Minnie's faces" (approximately 5.5 mm in the LCD display) during the measurement of accommodation. The specified target (faces) had good contrast (85% Contrast) and the target luminance was observed to be 15 cd/m^2 . This target was presented on a laptop whose display was cloned to a miniature LCD monitor.

Figure A1: Picture used for measuring binocular and monocular accommodation at frequent intervals.

Methods

Eleven participants between the ages of 7-14 years (Mean ± SD: 11 ± 2.34 yrs) with spherical equivalent refractive errors ranging from 0.5 to 1D (determined by cycloplegic refraction) participated in this study. All participants had best corrected visual acuity of 20/20 in each eye with normal binocular vision status and normal ocular health. Parental permission (from parents/guardians) and verbal assent (from study participants) were obtained before commencement of the study.

All participants wore their corrective lenses that provided a best corrected visual acuity of 6/6 in each eye. Accommodative response was determined for both the near targets placed at a distance of 33 cm from the eye. The responses were analyzed using the "Methods of agreement" proposed by Bland and Altman to determine the 95% limits of agreement between the two targets. Paired t-test was also performed to compare the responses obtained with two different targets

Results

Figure A2 (a) shows the mean accommodative response determined with two near targets. It can be seen that the accommodative response determined using a picture target were on average 0.25D less than those obtained using high contrast text (Text: -2.42 ±

0.46D; Picture: -2.17 ± 0.47D; t= 2.6; P = 0.02). However, Figure A2 (b) indicates that the trend towards a lower accommodative response was not noticed in all study participants with some participants even showing a greater accommodative response with the picture target.

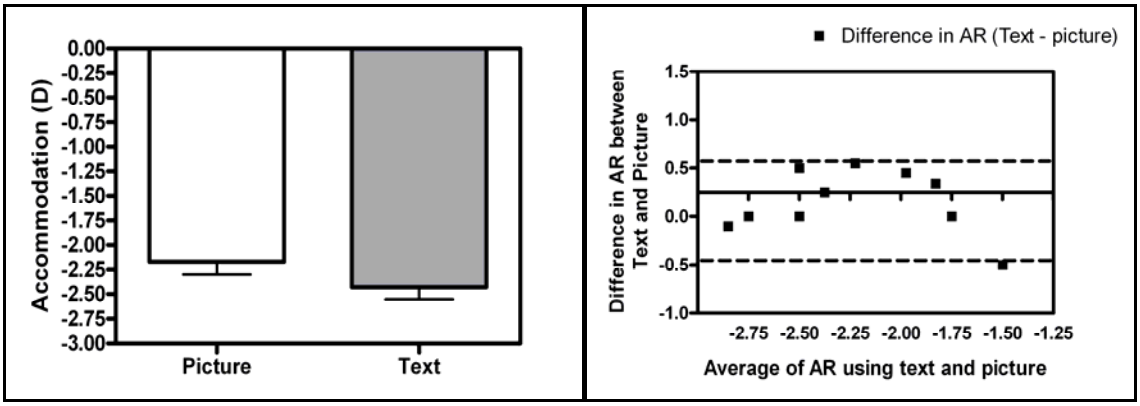


Figure A2 (a- left): Mean accommodation response determined using two different accommodative targets. The picture target, on an average showed 0.25D lesser response than the text. Figure A2 (B-right): Bland and Altman plot for determining agreement between the two near targets. The dotted lines indicate the 95% limits of agreement. No specific trend was observed in the accommodation response with a picture target when compared with a high contrast text.

Conclusion

The accommodative response obtained using a picture target was found to show a small but statistical difference when compared to a high-contrast text. However, since the magnitude was small and a specific pattern was not noticed, the picture target was acceptable for measuring accommodation.

Appendix 2: Validity and Repeatability of the modified Thorington method of estimating near phoria

Objective

1. To determine the validity of tangent scale designed for use with Modified Thorington technique (MTT) by comparing the near phoria measures with an objective test of ocular deviation.
2. To determine the repeatability of the MTT by comparing responses obtained on two separate occasions.

Methods

Eleven participants between the ages of 7-14 years (Mean ± SD: 11 ± 2.34 yrs) with spherical equivalent refractive errors ranging from 0.5 to 1D (determined by cycloplegic refraction) participated in this study. All participants had best corrected visual acuity of 20/20 in each eye with normal binocular vision status and normal ocular health. Parental permission (from parents/guardians) and verbal assent (from study participants) were obtained before commencement of the study.

All participants wore their corrective lenses that provided a best corrected visual acuity of 6/6 in each eye. Horizontal near phoria was assessed at 33cms using the techniques elaborated below:

Modified Thorington technique:

Modified Thorington technique was performed using a custom designed tangent scale. The tangent scale consisted of a small central hole with a horizontal row of letters/numbers on either side of the hole. The letters/numbers on scale were approximately 3.5 mm high, which is equivalent to a Snellen fraction of approximately 6/15 (at that distance). Each letter/number was separated by 1ΔD (3.3 mm apart) at a distance of 33cms with numbers representing exodeviations and letters indicating esodeviations. A Maddox rod was placed in front of the right eye with grooves aligned horizontally creating a vertical streak of line. Participants wore their corrective lenses (if required) and were instructed to fixate at the zero on the center of the tangent scale, maintain the letters clear and report the number or the letter that was closest to the red line. The same technique was repeated thrice and the average of three responses indicated the participant's heterophoria at 33cms.

Prism-neutralized objective cover test

Prism-neutralized cover test was performed with full room illumination including over-head stand lighting. Participants wore their corrective lenses and were instructed to fixate on a single letter approximately 4 mm high, equivalent to a Snellen fraction of approximately 6/15 at 33cms. An occluder was alternately moved between the eyes when the participant maintained steady fixation at the near target. The amount and direction of ocular movement was noted and loose prisms with appropriate base direction were held close to the participant's right eye while alternate cover test was repeated. The magnitude of the prism was increased until reversal of ocular movement was seen. The magnitude of prism that showed reversal and the magnitude that still showed the deviation were averaged and taken as the near phoria measure.

Repeatability assessment:

To examine the repeatability of the MTT, the near heterophoria obtained with MTT was re-assessed on a different day using the same technique mentioned above.

Results

The Bland and Altman Technique (Bland et al., 1986) was used to determine the 95% limits of agreement (Mean $_{(diff)}$ ±1.96*stdev $_{(diff)}$) for comparison of the different testing methods and also the repeatability test. Figure A3 (i) shows that the mean near phoria (CT: 3.7 ± 2.5 ΔD; MTT: 3.4±2.5 ΔD; t = 1.9; P >0.05) was similar between both the methods. Figure A3(ii) shows good agreement between MTT and Cover test with 95% limits of agreement ranging between ± 1.05 ΔD (p>0.05) suggesting that phoria obtained using MTT could be 1.05ΔD higher or lower than the objective estimation with alternate cover-test.

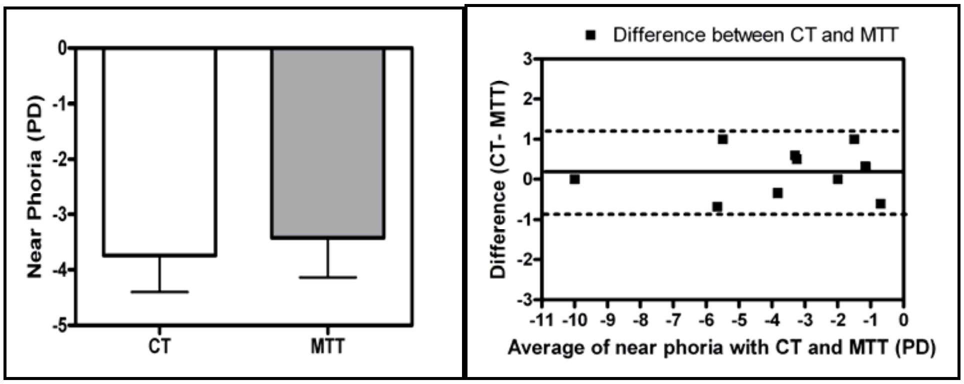


Figure A4 shows the comparison between phoria response obtained with CT and MTT.

Figure A4 shows the repeatability of near heterophoria using the modified Thorington Technique. The co-efficient of repeatability (COR) of MTT was found to be ±1.98 ΔD similar to results found in previous studies (Escalante & Rosenfield., 2006). Thus any change in phoria greater than ± 2 ΔD will be considered a clinically significant change in the measurement.

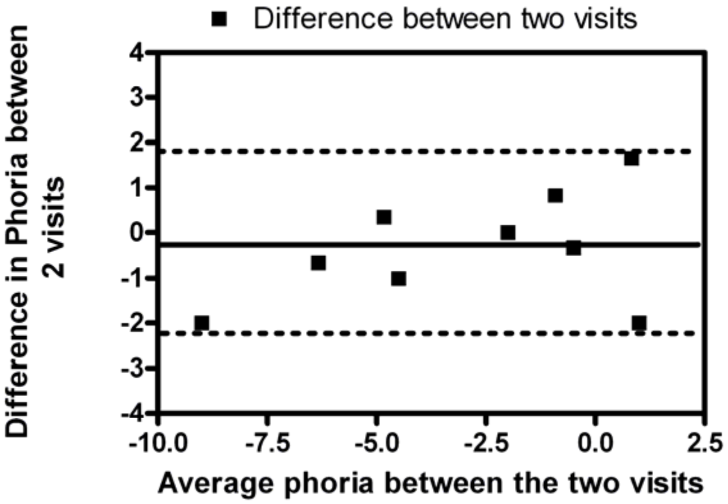


Figure A5 shows a plot of average and mean differences in phoria determined on two separate sessions to estimate repeatability of phoria measures using MTT .The COR was found to be ±1.98Δ

Conclusion

In light of its good accuracy; repeatability and simpler test instructions and possibility of obtaining faster measurements that can be easily comprehended by a child, MTT was chosen to measure horizontal near heterophoria in the current investigation.

Appendix 3: Deviation of gaze and measurement of accommodation

Purpose

Off-gaze measurements are known to result in erroneous measurement of refraction due to the contamination of measures by off-axis astigmatism (Millodot & Lamont., 1974). We wanted to identify a method for accurate measurement of accommodation when participants fail to fixate at the target resulting in off-axis errors.

Method and Results

The monocular mode of the Power Refractor (screen dump shown in Figure 5) provides vertical meridional refraction coupled with measures of deviations in gaze and pupil diameter. The gaze tracker (right corner in Figure 5) provides information about horizontal and vertical changes in gaze direction while the participant fixates on the target. For the purpose of this thesis, off-axis errors were defined as horizontal deviations greater than 10 degrees and vertical deviations greater than 5 degrees of fixation. This criteria has been recommended by the manufacturer (PowerRefractor manual) and has also been used in several studies performed with this instrument (Allen et al., 2003; Choi et al., 2000)

During measurement of accommodation, the examiner constantly monitors the gaze position. If deviations greater than 5deg vertical or 10 deg horizontal are noticed, the examiner immediately identifies the region with a flag (keyboard input – PowerRefractor) and instructs the participant to fixate at the target. In case of child participants, deviations in gaze were also seen because of improper positioning of their head on the chinrest. An additional helper made sure that the participant’s head is positioned appropriately on the chin rest. Upon regaining fixation at the target (defined as vertical and horizontal deviations less than 5 and 10 degrees respectively) a second flag was marked on the response. Figure 26 (a) and (b) shows a typical example of off-gaze errors obtained when measuring accommodative response from an 8 yr old participant. The increased vertical gaze deviation and its effect of the accommodative response can be seen from Figure 26.

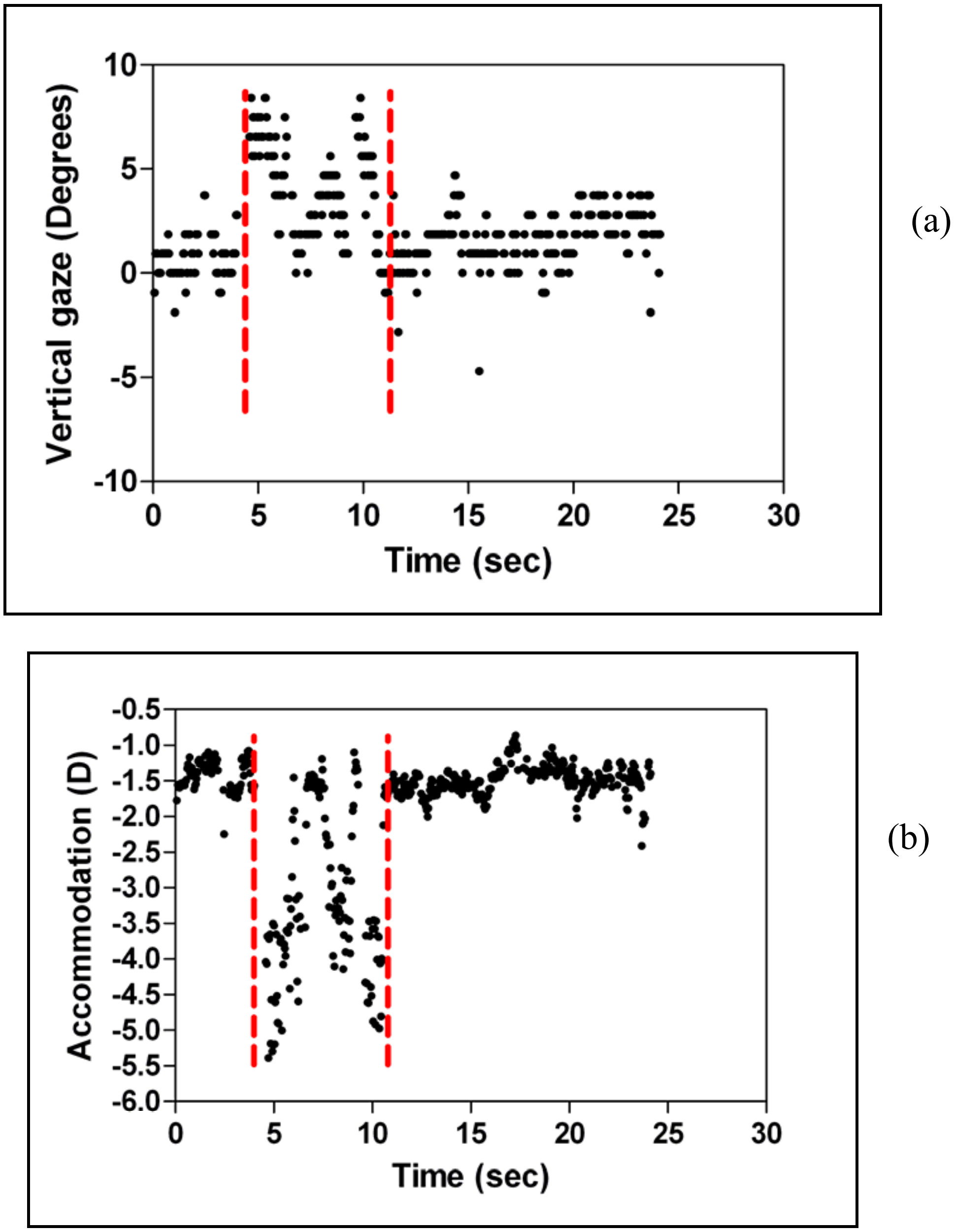


Figure 26: Increased vertical gaze errors (a) and its effect of accommodative response (b) during continuous measurements with the Power Refractor.

The figure demonstrates that an increase in vertical deviation greater than 5 degrees resulted in highly variable accommodative responses which if included would result in an erroneous response. Thus these regions (within the two flags) were excluded from the data before averaging the accommodative responses.

Conclusion

A method was identified to exclude any accommodative data contaminated by off-gaze measurements. The regions of improper fixation were identified as “flags” and were excluded before averaging of the accommodative response.

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