Binocular adaptation to near addition lenses in emmetropic adults

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Abstract

Near addition lenses are prescribed to pre-presbyopic individuals for treatment of binocular motor problems such as convergence excess and to control the progression of myopia. To date, no investigation has looked at the complete sequence of binocular motor responses during a period of near work with +2D lenses. This investigation evaluated changes to accommodation and vergence responses when young adults sustained fixation at 33 cm with +2D addition lenses. In addition, the effect of the accommodative vergence cross-link (AV/A) on the magnitude and the completeness of binocular adaptation to these lenses were evaluated. The results showed that +2D lenses initiate an increase in exophoria and convergence driven-accommodation. The degree of the initial induced phoria was dependant upon the magnitude of the AV/A ratio. Vergence adaptation occurred after 3 minutes of near fixation and reduced the exophoria and convergence driven-accommodation. The magnitude of vergence adaptation was dependant upon the size of the induced phoria and hence the AV/A ratio. The completeness of adaptation was seen to vary inversely with induced exophoria and thus the AV/A ratio.

Keywords: Near adds; vergence adaptation; accommodative-vergence crosslink; near work; accommodation

1 Introduction

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 including treatment of convergence excess (Scheiman & Wick, 1994b), alleviating near point visual stress (Birnbaum, 1985; Gruning, 1985; Birnbaum, 1993) or for attenuation of myopia progression (Roberts & Banford, 1967; Oakley & Young, 1975; Greenspan, 1981; Leung & Brown, 1999; Gwiazda et al., 2003). The basis for prescribing plus lenses has been to control accommodation and/or accommodative vergence. Several investigations have been carried out in pre-presbyopic adult participants to evaluate the precise effect of these lenses on accommodation (Rosenfield & Carrel, 2001; Seidemann & Schaeffel, 2003; Shapiro, Kelly, & Howland, 2005; Easwaran, 2005; Jiang, Tea, & O'Donnell, 2007). Accommodative responses have been measured under both binocular and monocular viewing conditions through different magnitudes of plus lenses ranging from +0.75D to +3.00D. The results of these investigations consistently show that near addition lenses reduce the lag of accommodation with lower dioptric powers (+0.75 to +1D) (Rosenfield & Carrel, 2001; Seidemann & Schaeffel, 2003; Easwaran, 2005) and have even brought about a lead of accommodation with higher dioptric powers (+2 and +3D) (Rosenfield & Carrel, 2001; Seidemann & Schaeffel, 2003; Shapiro et al., 2005; Easwaran, 2005; Jiang et al., 2007). Most of these studies have measured accommodation: immediately after lens insertion (Rosenfield & Carrel, 2001; Seidemann & Schaeffel, 2003; Shapiro et al., 2005; Easwaran, 2005; Jiang et al., 2007), after a period of near work (Shapiro et al., 2005), or have measured accommodation alone during near work (Easwaran, 2005). Similar studies have documented the effect of these lenses on the vergence system alone either immediately after the addition of lenses (Maddox & Edin, 1893; Schor, 1979b) or with sustained fixation (North & Henson, 1985).

The addition of near adds will affect both accommodation and vergence systems as they are linked through accommodation vergence (AV) and vergence-accommodation (VA) cross links where optically stimulated accommodation evokes convergence (Maddox & Edin, 1893; Alpern, Kinkaid, & Lubeck, 1959) and vice-versa for disparity stimulated vergence (Fincham & Walton, 1957). Based on current models of accommodation and vergence (Hung & Semmlow, 1980; Schor, 1986) it is expected that the introduction of near addition lenses will reduce the demand on accommodation and will lead to a reduction in accommodative convergence thereby inducing a relative exophoric shift. This divergence is then compensated by increasing convergence and convergence accommodation through the VA cross-link thus increasing the overall accommodative response. When viewing is prolonged, it is expected that adaptation of the vergence response will occur thereby reducing the vergence error and the demand on the "fast" fusional vergence controller (Schor, 1979b). Models differ in their prediction for the resulting change in accommodation based on the location of the cross-links. Those models that place the crosslink before the tonic component (Schor, 1986; Schor, 1992) predict that VA would be reduced after vergence adaptation; however, others (Ebenholtz & Fisher, 1982 supported by Rosenfield & Gilmartin, 1988) predict no change since their model places the cross-links after the tonic component.

Adaptation to ophthalmic lenses has been investigated by North and Henson (1985) in 4 adult subjects at both distance and near fixation. Near heterophoria (at 40 cm) was measured every 15 sec for the first 3.5 minutes of binocular viewing through +2D lenses, followed by single measures at 33.5 minutes and 66.5 minutes of binocular viewing. The degree and time course of adaptation to plus lenses were found to depend on the magnitude of the exophoria induced by the lenses. 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. Individuals with larger induced phorias did not show complete adaptation even after 1 hour of binocular viewing. If vergence adaptation is considered as a process which serves to reduce the output of convergence driven accommodation, then the incomplete adaptation observed in the individuals with larger induced phorias might be due to the need for higher binocularly driven accommodation in order to reduce the lag of accommodation. The study by North and Henson (1985) only evaluated the vergence and not the accommodative response with addition lenses. The influence of the accommodative response on vergence adaptation and vice-versa in individuals with different AV/A ratios is not clearly known.

It would appear that adaptation to a near addition lens is non trivial for a pre-presbyope given their active accommodation when compared to a presbyope. However, despite the widespread use of near adds for various conditions a complete evaluation of the binocular motor responses during sustained binocular viewing has not been conducted so far. Accordingly, the purpose of this study was to investigate the changes to accommodation and vergence systems while pre-presbyopic adults perform near work at 33 cm with +2D lenses for a period of 20 minutes. An additional aim was to determine whether the accommodative vergence cross-link (AV/A ratio) impacted the magnitude and time course of adaptation to near addition lenses.

2 Methods

2.1 Study participants

Eleven adults between the ages of 20 and 29 years (Mean ± SD = 23.3 ± 2.39 yrs) were recruited from the student / staff population at the School of Optometry, University of Waterloo. The experiment was performed with written consent obtained from all participants. The study was approved by the Office of Research Ethics, University of Waterloo and followed the tenets of the Declaration of Helsinki.

All participants had normal general & ocular health and underwent a preliminary examination to ensure the following: emmetropic refractive error (defined as a refractive error between -0.5 to +.0.75D); visual acuity of at least 6/6 in each eye; astigmatism less than 1D; anisometropia less than 0.5D; normal amplitudes of accommodation; and that participants were not taking any medications that might influence the accommodation and vergence systems (Westheimer, 1963). Binocular visual status was verified by ensuring normal distance and near phorias (Morgan, 1944) and normal near point of convergence. A measure of gradient AV/A ratio was also obtained by determining the change in near phoria with the addition of +1D lens. The mean AV/A ratio of the study group was found to be 3.03 ± 0.3 Δ/D.

2.2 Instrumentation and experimental setup

Fig.1 shows a schematic of the experimental apparatus that facilitated the measurement of accommodation and vergence at a near fixation distance of 33 cm. The following sections describe in detail the instrumentation, targets and procedures employed to measure changes to both the ocular motor systems over time.

<INSERT FIGURE 1 HERE>

2.2.1 Measurement of accommodation

Accommodative measures with and without +2D lenses were obtained using the monocular mode of an eccentric infra-red (IR) photorefractor, the PowerRefractor (MultiChannelSystems, Reutlingen, Germany) (Gekeler, Schaeffel, Howland & Wattam-Bell, 1997; Choi et al., 2000). This setting of the instrument determined refraction along the vertical meridian of the participants' right eye, sampling at a rate of 25 Hz coupled with measures of gaze deviations and pupillary diameter. When tested with near addition lenses, the PowerRefractor recorded accommodative measures as a sum of the spectacle lens and the actual accommodative response. For example, the PowerRefractor would show a reading of 3.25D when a participant accommodates 1.25D when fixating a 33 cm target through +2D lenses. In this investigation, we used a term plane of focus to represent this combination of lens power and accommodative response. The accommodative measures obtained from the PowerRefractor were calibrated by conducting a two-step protocol similar to the method used in previous studies (Seidemann & Schaeffel, 2003; Blade & Candy, 2006) to ensure the accuracy of the response. Based on the results of the calibration study (described in appendix A) all Power Refractor responses (PR) were adjusted by a calibration equation to define actual plane of focus response (PF) where

$$PF = (PR / 1.02) - 0.22 \qquad (1).$$

2.2.1.1 Near targets for stimulating accommodation

Two high contrast and colorful near targets were used to sustain and measure closed-loop accommodation. The "sustaining target" was a cartoon movie displayed using a digital video disc (DVD), chosen in an attempt to avoid boredom that might occur due to prolonged near fixation with conventional text. The "measuring target" was a color cartoon slide presented using a laptop computer, chosen so that the accommodative measures would be taken from a similar stimulus rather than a unique target such as a row of letters. The same slide was always used for measurement as it was necessary to maintain the same stimulus characteristics for each accommodative measure. The cartoon slide used for stimulating accommodation measured approximately 5.5 mm with good contrast (85%) and a target luminance of 15 cd/m^2. This target was compared to high contrast (92%) text in 11 participants and demonstrated similar accommodative responses that were statistically insignificant when compared to the conventional text (Cartoon: -2.24 ± 0.22D; Text: -2.35 ±0.32D; P>0.05).

Information from the two near displays (DVD player and Laptop computer) were sent to a custom-designed control box (Control Box, Fig. 1) whose output consisted of a miniature liquid crystal display (LCD) monitor (Model No: LT-V18 U; Victor company of Japan) mounted onto an optical bench (Fig 1). The presentation of near targets (movie or cartoon slide) to the LCD monitor was controlled using a toggle-key. This setup, with synchronization of both the near targets into the control box helped maintain a constant screen size and facilitated rapid change between the targets to enable quicker measurements. The image from the monitor was then projected at a distance of 33cms through a semi-silvered mirror (SM, Fig. 1). The LCD monitor was 1.77″ wide and subtended 3.5 deg x 2.3 deg (H x V) which enabled the gaze deviations to be kept within 5 degrees of fixation and thus prevented any significant off axis measurements (Ferree, Rand, & Hardy, 1931; Millodot & Lamont, 1974).

Binocular and monocular measures of accommodation were recorded continuously for a period of 10sec after confirming steady fixation using the gaze control function displayed on the PowerRefractor interface. Binocular accommodation was measured when both eyes fixated the target; however, measures were recorded from the right eye alone. For measurement of monocular accommodation, the left eye was occluded. Under both viewing conditions, accommodative responses were obtained for an additional 5 sec period if the gaze errors exceeded 5 degrees of fixation (Ferree et al., 1931; Millodot & Lamont, 1974). The intervals of unsteady fixation were identified by the examiner and flagged using keyboard inputs. These regions were then excluded during data analysis.

In addition to the measurement of closed loop accommodation, open loop tonic measures of accommodation were also 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 (DOG target, Fig 1).

2.2.2 Measurement of phoria

The horizontal near heterophoria was measured using the modified Thorington technique – MTT (Borish, 1975) and the magnitude of the phoria was quantified using a custom designed tangent scale (TS, Fig 1) placed at 33cm. The TS consisted of a small central aperture 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 (1Δ apart at a distance of 33cm). The scale was illuminated using three white light emitting diodes (LED) housed inside a rectangular box providing a background luminance of 10 cd/m^2. The TS was also connected to the control box (Fig 1) which facilitated the measurement of the phoria by illuminating the scale and simultaneously turning off the LCD monitor to avoid stray light affecting the visibility of the TS.

The accuracy of the scale was evaluated by comparing the MTT measures with an objective - prism neutralized alternate cover test and the repeatability of the technique (MTT) was assessed by repeating measures on a separate occasion (described in appendix- 2). The results demonstrated good accuracy of the scale compared to the cover test and also showed good repeatability with a coefficient of repeatability (CR) of 1.98 Δ. Similar results (good repeatability and validity) with the MTT have been reported by previous studies (Schroeder et al.,1996; Casillas Casillas & Rosenfield, 2006; Escalante & Rosenfield, 2006).

The measurement of near phoria was performed by instructing the participants to fixate the center of the tangent scale and maintain the "zero" (on the TS) clear during the measurement. An occluder was placed in front of the right eye (A flashing technique similar to the method used by Henson & North (1980)) to prevent voluntary fusion. A Maddox rod (grooves aligned horizontally) was inserted during this period of occlusion. After 10 sec (mental count) the occluder was removed and the participant was instructed to verbally report the number/letter that was closest to the red line. The same technique was repeated thrice and the near heterophoria was defined as the average of the three responses.

2.2.3 Experimental procedure

The experimental procedure consisted of two study sessions; one session was performed with the participants wearing their corrective lenses if any, determined during subjective refraction (referred to as "no lens condition") and the other involved measurements with +2D lenses (referred to as "lens condition") added over their 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 two study sessions were performed on different days (separated at least by 24hrs) and the order of testing was randomized to avoid bias.

Prior to the start of the study sessions, all participants were dark adapted for 3 minutes (Wolf, Ciuffreda, & Jacobs, 1987) to avoid effects of previous near work. The lighting in the examination room was then reduced to approximately 10 lux to obtain sufficiently large pupil sizes (greater than 4mm as recommended by the manufacturer of PowerRefractor) for the measurement of accommodation.

Each session involved measurement of pre-task tonic accommodation (immediately after dark adaptation), followed by baseline measurement of phoria (vergence open loop), binocular and monocular accommodation (closed loop). The time taken for one complete measurement block (measurement of phoria, binocular and monocular accommodation) was estimated to be 1.05 ± 0.20 minutes (Mean ± SD). Following the baseline measurement, participants were instructed to watch the cartoon movie, and subsequent measures of phoria, binocular and monocular accommodation were recorded after 3, 6, 9, 15 and 20 minutes. Post-task tonic accommodation was then measured immediately after the 20 minute near task.

Analysis of PowerRefractor Data

The accommodative response at each time point was estimated by averaging the data points obtained over the measurement period (normally 10 sec) in the following manner. The raw data obtained over the measurement period were exported to an Excel spread sheet. Columns contained data listing the plane of focus (accommodation), pupil diameter and gaze positions. Data was obtained every 40msec thereby providing 250 rows of data for each 10 sec sample. Each row of data 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. Blink artifacts were determined by inspecting a break in the recorded response which was accompanied by increased myopic refractions and reduction in pupil diameter. The myopic shift in refraction is speculated to be due to the reduction in pupillary diameter affecting the intensity gradient of the reflex (Allen, Radhakrishnan, & O'Leary, 2003). These erroneous values were manually removed by deleting one row before and after the blink (total of 2 rows) similar to a criterion used by previous investigators (Allen et al., 2003). This resulted in discarding approximately 2% of the data. To be considered for averaging and further analysis, each participant needed to have at least 200 rows of acceptable data after satisfying all the above criteria. The data retained were averaged to obtain the plane of focus response for a particular time point. Since information from two participants failed to provide the minimum levels of acceptable data as a result of pupil diameters less than 4mm, their data was excluded from the averaging process.

2.2.4 Effect of AV/A ratio on vergence response with +2D lenses

To determine the effect of accommodative-vergence cross link (AV/A) on the vergence response with +2D lenses, stimulus and response AV/A ratios of participants (N = 9) were determined from the experimental results (with +2D lenses) using the Gradient AV/A method (Borish, 1975). The change in phoria responses over time were then studied based on the magnitude of AV/A ratio.

2.2.5 Statistical analysis

Repeated measures analyses of variance (RM-ANOVA) was used to determine the effect of lens condition and time on accommodation and vergence. 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 the 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).

3 Results

3.1 Accommodative response with and without near addition lenses

Fig. 2 shows the plane of focus measures obtained during the no lens (dotted lines) and +2D lens viewing conditions (solid lines). As discussed, the plane of focus represented the participants' accommodation in the no lens condition and the combination of lens power and accommodation under the lens viewing condition through the near add. Fig 2 demonstrates that the presence of the +2D add shifted the plane of focus significantly ($P < 0.001$) under both binocular and monocular viewing conditions. Since the accommodative demand and lens power were kept constant, all changes in the plane of focus represent accommodative changes. The pattern of change of these measures over time varied significantly depending upon the type of lens condition (no lens/lens viewing condition).

<INSERT FIGURE 2 HERE>

3.1.1 No-lens condition

During the no lens condition (Fig. 2, dotted lines) the participants' on average, exhibited initial lags of accommodation (binocular: 0.59 ± 0.07D; Monocular: 0.73 ± 0.10D) which were seen to reduce significantly over time (mean reduction in lag after 20 minutes of near work- Binocular: 0.13 ± 0.08 D; monocular 0.16 ± 0.07D ; $P<0.05$). During the sustained viewing condition, the binocular accommodative response was seen to consistently exceed the monocular response (Table 1; $P>0.05$) but the pattern of change was similar in form under both viewing conditions.

3.1.2 Lens condition

Binocular and monocular focus with +2D lenses (Fig 2, solid lines) varied in terms of the initial response and the pattern of change over time. The introduction of +2D lenses resulted in a mean monocular plane of focus response (Fig 2, solid line with squares) which was almost equal to the position of the target (33cm, 3D - dashed line in Fig. 2). However, the plane of focus exceeded the demand by 0.43 ± 0.14 D (exhibiting a lead of accommodation) in the binocular viewing condition (Fig. 2, solid line with triangles). This difference in focus between the two viewing conditions at onset was found to be statistically significant (Difference: -0.51 ± 0.10D; $P<0.01$; table 1). During sustained near fixation the binocular focus alone showed a significant reduction after 3 minutes of near work (Fig. 2, solid line with triangles: Magnitude of reduction: 0.26D; post-hoc $P<0.01$) with no further reduction observed beyond this time point. The monocular plane of focus measures remained stable with no significant changes throughout the 20 minute near fixation period (Fig. 2, solid line with squares; post-hoc tests: $P>0.05$). The difference between binocular and monocular focus was not found to be significant after 3 minutes of binocular viewing (Table 1)

<-INSERT TABLE 1 HERE>

3.1.3 Tonic accommodation

Fig.3 illustrates the differences in tonic accommodative responses (measured with the DOG target) before and after the 20 minute near task, during both no lens and lens viewing conditions. Prolonged near work resulted in an increase in tonic accommodation (increased negative shift of 0.37± 0.07D) that was found to be significant ($P <0.05$) in the no lens condition. Viewing with near addition lenses found small changes (0.05 ± 0.06D) in the opposite direction; however these were not significantly different ($P >0.05$).

<INSERT FIGURE 3 HERE>

3.2 Vergence response with and without near addition lenses

The average habitual near phoria of the adult sample prior to the experiment was observed to be -3.87 ± 0.76Δ (with negative sign indicating exophoria). Fig.4 illustrates the change in the mean near phoria during prolonged near work, with and without the near addition lenses. The mean phoria in the no lens condition was quite stable and did not show any statistically significant difference even after 20 minutes of near work (Fig. 4, solid line with circles: $P>0.05$).

<INSERT FIGURE 4 HERE>

Introduction of +2D lenses significantly increased the mean near exophoria (Fig 4, solid line with squares) with the greatest increase seen upon lens insertion (time point 0: Magnitude: 5.82 ± 0.70 Δ; $P<0.01$). Continued near fixation resulted in a significant reduction in the mean exophoria following 3 minutes of binocular viewing (Fig. 4, solid line with square; Magnitude of reduction: 3.43 ± 0.69 Δ; $P<0.001$).With extended binocular fixation the mean exophoria reduced in an asymptotic manner up to 20 minutes of binocular viewing (Difference between 3 & 20 min time points: 1.07 ± 0.76Δ; $P<0.05$). It is evident that the pattern of change in phoria over time is different compared to the no lens condition (Fig.4, solid line with circles; $P<0.001$); however, this asymptotic pattern of change was similar to changes observed in binocular focus with the near add (Fig 2, solid line with triangle). A statistically significant correlation was observed between the reduction in binocular focus and the reduction of exophoria over prolonged binocular viewing at the near task (Pearson $r>0.9$; $P<0.05$).

3.2.1 Magnitude and time constant of reduction in exophoria

The changes in near phoria over time with +2D lenses were plotted using an exponential decay function that was fit to determine the magnitude and time constant of phoria reduction (Fig.4, broken line). This function provided an R^2 value of 0.9. The mean magnitude of change in vergence (ΔV), defined as the total reduction in phoria upon saturation, was found to be 4.40 ± 0.21 Δ. The time constant, defined as the time taken to reach 63% of total reduction in exophoria was found to be 2.10 ± 0.11 minutes on an average for the study group. An additional parameter, the "percentage of completeness (PC)"of phoria reduction was then calculated by dividing the amount of phoria reduced over time (ΔV) by the initial change in phoria induced by the +2D lens (ΔIP). The "completeness factor" after 20 minutes of prolonged near viewing was found to be only 76% (PC = (4.4Δ/ 5.8Δ)*100) indicating that adaptation was not complete even with sustained binocular fixation.

3.3 Effect of AV/A ratio on the reduction of exophoria

The mean stimulus and response AV/A ratios (with +2D lenses at time 0) from 9 emmetropic participants were found to be 2.83 ± 0.27 Δ/D and 4.22 ± 0.32 Δ/D respectively. The stimulus AV/A ratio with +2D lenses was found to be similar to the clinical gradient AV/A ratio obtained during the preliminary assessment with +1D lens (Stimulus AV/A with +1D: 3.03 ± 0.30Δ/D; $P>0.05$); however, the response AV/A ratio was found to be significantly greater than both the stimulus AV/A measures ($P<0.05$). The association between the stimulus and response AV/A ratios was found to be strong with a statistically significant positive correlation (Pearson r = 0.71; $P<0.05$) indicating that the majority of participant's who exhibited a higher stimulus AV/A ratio also exhibited a higher response AV/A ratio.

3.3.1 Relationship between AV/A and magnitude of reduction in exophoria

The total change in exophoria upon saturation (ΔV) was determined in each participant by fitting an exponential function to their phoria responses with +2D lenses. These responses (ΔV) were then plotted as a function of their respective stimulus AV/A ratios to determine the relation between the magnitude of reduction in exophoria and AV/A ratio. Correlation analysis indicated a strong and significant positive relation between the two variables (Fig. 5, Pearson r = 0.78; P<0.01) signifying that higher AV/A ratios are associated with higher magnitudes of reduction in exophoria after the near task.

<INSERT FIGURE 5 HERE>

Further, for illustrative purposes, the effect of AV/A ratio on the time course of phoria change (Fig 6) was also evaluated by comparing mean changes between individuals with the three highest (High AV/A group) and the three lowest AV/A ratios (Low AV/A group). The average lens induced exophoria was found to be 4.00 ± 0.47Δ and 7.16 ± 0.42Δ for the low and high AV/A groups respectively. It can be seen that both the groups produce a similar pattern of reduction in exophoria with the greatest, statistically significant reduction occurring within the first 3 minutes of binocular viewing (Fig 6; High AV/A: 3.50 ± 0.30 Δ; Low AV/A: 2.83 ± 0.68 Δ). The "percentage of completion" (PC = ΔV/ΔIP) after 3 minutes of near task was calculated to be 71% for the low AV/A group and 48% for the high AV/A group. After 20 minutes of binocular viewing, the group with smaller AV/A showed close to complete reduction of the induced phoria (89%) compared to only 74% reduction in the group with the higher AV/A ratio (P<0.05). The total magnitudes of reduction in exophoria (determined by the saturation values of the exponential fit) were found to be statistically significant (P < 0.001) between the two groups with the greatest magnitude of reduction observed in the high AV/A group (Fig.6; Magnitude of adaptation: Low AV/A = 3.23 ± 0.11 Δ; High AV/A = 5.28 ± 0.06 Δ). The time constants of reduction in exophoria were also found to be statistically significant (Low AV/A = 1.58 min; High AV/A = 2.70 min;, P <0.05) indicating that individuals with higher AV/A ratios take a longer time to attain 63% of total reduction compared to those with lower AV/A ratios.

<INSERT FIGURE 6 HERE>

Plane of focus measures from the two AV/A groups were then analyzed to locate any differences in accommodative response between the groups. Accommodative measures with +2D lenses showed a trend similar to the overall analysis (Fig. 2 solid lines) with significant reduction in binocular focus alone concomitant with the reduction in exophoria. A 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 AV/A groups (Low AV/A: 0.27D; High AV/A: 0.33D; $P > 0.05$). Additionally, the correlation between reduction in binocular accommodation and AV/A ratio was also found to be insignificant (Pearson $r = 0.6$; $P > 0.05$)

4 Discussion

The results of this investigation provide information on the synchronous changes of the accommodation and vergence systems when pre-presbyopic individuals perform sustained near activity through plus lenses. The forthcoming sections discuss the findings of this study and illustrate the consistency of the results with current models of accommodation and vergence (Hung & Semmlow, 1980; Schor & Kotulak, 1986; Schor, 1992).

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

The introduction of +2D near addition lenses resulted in three immediate changes to the ocular motor system: Both the binocular and monocular plane of focus increased resulting in an elimination or reversal of retinal defocus such that any defocused image was now in front of the retina; There was an increase in exophoria and significantly greater differences between the magnitudes of binocular and monocular focus. The increase in plane of focus and its position at or slightly in front of the near target are similar to the results observed in previous studies with adds of this magnitude (Rosenfield & Carrel, 2001; Seidemann & Schaeffel, 2003; Shapiro et al., 2005; Easwaran, 2005; Jiang et al., 2007). Though the plane of focus responses with +2D lenses are higher than the no-lens condition, it should be noted that the accommodative response itself had declined with the addition of +2D lenses. This caused the relaxation of accommodative vergence resulting in an increase in exophoria in accordance with the participant's AV/A ratio. The mean exophoria ($5.82 \pm 0.70\ \Delta$) induced by the +2D lenses is also consistent with previous empirical findings (Maddox& Edin, 1893; Schor, 1979b; North & Henson, 1985; Jiang et al., 2007).

The greater difference between the binocular and monocular focus and the over-driven binocular focus immediately upon lens viewing can both be attributed to an increase in convergence accommodation. This finding draws support from the models of accommodation and vergence (Hung & Semmlow, 1980; Schor & Kotulak, 1986; Schor, 1992) as follows: Under binocular viewing conditions, the lens induced exophoria would trigger the fusional vergence system to produce an increase in reflex convergence through negative feedback mechanism (Schor & Kotulak, 1986). The increased fusional convergence, in turn drives an immediate increase in binocular focus through the convergence accommodation crosslink (Fincham & Walton, 1957; Schor & Kotulak, 1986; Schor, 1992). This then leads to the increase found in the overall plane of focus measure obtained in the binocular viewing condition. Previous studies have reported similar results demonstrating consistently greater binocular measures of accommodation compared to monocular measures (Seidemann & Schaeffel, 2003; Shapiro et al., 2005; Jiang et al., 2007).

4.2 Vergence adaptation and reduction of vergence accommodation

This is the first investigation which reports on the simultaneous changes to both the accommodation and vergence systems during a period of prolonged near work with +2D addition lenses. Vergence and accommodative measures over time revealed a significant reduction in both the lens induced exophoria and the binocular focus within 3 minutes of fixation at the near task. The change in these responses over time can be attributed to “vergence adaptation” (Ogle, 1950; Schor, 1979a; North & Henson, 1985). 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 from the current experimental results that the fast component mediated the initial increase in fusional convergence in response to the increased exophoria produced by plus lenses. With prolonged binocular viewing, the fast fusional vergence provided the input to the slow fusional component. The slow component gradually replaces the fast convergence increasing the tonic levels of convergence which thereby reduces the exophoria and convergence driven 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 the models (Schor & Kotulak, 1986; Schor, 1992) that suggest reduction of cross-link interactions upon adaptation of the respective ocular motor system (for example adaptation of the accommodation would reduce the fast component and result in a reduced AV gain-(Jiang, 1996)). Additionally, the reduction in exophoria following prolonged binocular viewing could have occurred if there was a reduction in the AV cross link gain as a result of adaptation of accommodation. However, no evidence of an increase in tonic accommodation was found during lens wear and furthermore 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.

The steady decrease in the lens induced exophoria observed in this investigation agrees 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 79% after 3 and 20 minutes of binocular fixation respectively. The slight variation in the mean findings could be explained on the basis of differences in the accommodative-vergence components.

4.3 AV/A and phoria adaptation

The total amount of exophoria which reduced over time strongly depended on the magnitude of the AV/A ratio with greater magnitudes of adaptation occurring in individuals with higher AV/A ratios. 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 require greater amounts of vergence adaptation (Schor, 1979a). These results agree with previous studies (North & Henson, 1985; Schor and Horner, 1989) that have shown greater amplitudes of adaptation in individuals with higher AV/A ratios.

In addition to the differences in the magnitude of vergence adaptation, the current study also observed differences in completeness of adaptation between the low and high AV/A groups. While the magnitude of phoria adaptation was dependent upon the amount of induced phoria, phoria adaptation was not normally completed after 20 minutes of near fixation. Table 2 provides a comparison of the completeness of adaptation as a function of stimulus AV/A ratio in two studies (current study and North & Henson (1985) study - where stimulus AV/A ratios were obtained based on the induced phoria also taken using +2D lenses). The table illustrates the strong agreement between the two studies in a finding that demonstrates incomplete adaptation in individuals with higher AV/A ratios. This incomplete adaptation in individuals with higher AV/A ratios might have been purposeful in order to maintain some fast fusional vergence in place and thereby maintain a higher output of the binocular driven accommodative response for the purpose of reducing accommodative lag. However, the experimental results do not support this hypothesis since the monocular focus by itself is closer to the demand (3D) in the high AV/A group and complete adaptation is not expected to reduce the binocular focus below that of the monocular focus. In the current investigation we tested the change in adaptation for only 20 minutes of near work. It is possible that the higher AV/A group would show a more complete adaptation if the near viewing was prolonged. However, this possibility is also not very convincing since the reduction in phoria showed a plateau after 6 minutes of near work in majority of participants included for the analysis. Furthermore, the investigation by North & Henson (1985) did not show completeness in adaptation even after 60 minutes of binocular viewing in three individuals with high AV/A. Whether the adaptation response would achieve completeness with extended binocular viewing needs further investigation in a study involving greater range and magnitude of AV/A ratios.

<INSERT TABLE 2 HERE>

5 Conclusions and implications of the study

This investigation extends the understanding of the complete sequence of binocular response to near lens additions during sustained periods of near fixation and emphasizes the practical considerations for prescribing these lenses to pre-presbyopic individuals. The results demonstrate that the introduction of near addition lenses reduce the excessive lags of accommodation, initiates an increase in convergence and thereby increase the convergence driven accommodation. Vergence adaptation occurs within 3 minutes of binocular viewing, reducing both the need for fast fusional convergence and the output of convergence accommodation. The magnitude and completeness of vergence 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. Thus the results, consistent with both empirical findings and the models of the vergence and accommodation, underscore the need for robust vergence adaptation in children and pre-presbyopic adults.

The results of this investigation predict that individuals with near esophoria would need less of an adjustment as the near add would act to lessen the esophoria towards orthophoria thereby placing less demand upon reflex convergence. Furthermore, conditions of high esophoria, (convergence excess) can occur due to an abnormally high AV/A cross link (Scheiman & Wick, 1994b). Clinically it is perceived that the near addition serves to lessen the esophoria based upon the AV/A ratio. The binocular adaptation response in these individuals might be different than that observed in this experiment. The increase in divergence (reduced esophoria) following the addition of plus lens would not drive as strong a fusional convergence and the associated convergence accommodation response. Due to the reduced need for fast fusional vergence, the magnitude of vergence adaptation and thereby the accommodative reduction might not be the same as found in subjects with high AV/A studied in this investigation. An empirical investigation evaluating the binocular response in esophoric individuals would be appropriate.

Young adults and 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. When near adds are being prescribed in binocularly normal children for conditions like myopia control, it would be important to ensure that appropriate vergence adaptation has occurred.

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FIGURE LEGENDS- MAIN TEXT

Fig.1. Schematic of the experimental set-up: The participant (P) was seated at a distance of 1M from the PowerRefractor (PR). The two near targets (NT) for accommodation – sustaining target (Movie) and the measuring target (cartoon slide) were displayed on a miniature LCD monitor (M) using a custom designed control box. The control box was synchronized to receive input from the movie, cartoon slide and the tangent scale (for measurement of phoria) to facilitate rapid change between targets and enable faster measurement. The image from monitor (M) was projected at a distance of 33 cm using a semi-silvered mirror (SM). The tangent scale (TS) was also positioned at 33cm for the measurement of phoria. A Difference of Gaussian (DOG) target was placed at 3.5 M for opening the loop of accommodation.

Fig. 2. Mean plane of focus measures with (solid lines) and without +2D lenses (dotted lines) at 33cm (accommodative demand represented as dashed line at 3D). Under both conditions, filled triangles represent binocular responses and filled squares represent monocular responses. * indicates $P<0.01$ between the viewing conditions and $ indicates significant change ($P<0.01$) in binocular focus over time. Error bars indicate mean ± SE

Fig.3. Mean tonic accommodative change (Pre task – post task) with and without near addition lenses after 20 minutes of near work. * indicates $P<0.05$. Error bars indicate mean ± SE

Fig.4. Mean phoria responses with (solid line with squares) and without (solid line with circles) +2D lenses during 20 minutes of near fixation. Broken line illustrates the exponential fit of changes in near phoria with addition lenses. * indicates $P<0.001$; $ indicates $P<0.05$. Error bars indicate mean ± SE

Fig.5. Plot showing the relation between stimulus AV/A ratio and total change in phoria (ΔV) upon saturation in each participant.

Fig.6. Comparison of the change in phoria responses between high (solid line) and low AV/A ratios (dotted line). The ordinate of the graph illustrates the phoria response normalized to their baseline induced phoria and abscissa shows time in minutes. * indicates $P<0.05$ when magnitude and time constant of reduction in exophoria were individually compared between the two groups.

APPENDIX A AND B: FIGURE LEGENDS

Fig.A1. Absolute calibration (a): - Comparison of accommodation response with PowerRefractor and retinoscopy at two different distances. Figure A1 (b) shows a plot of the average accommodative response obtained using the two methods vs. the 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 similar trend towards hyperopic estimation was observed for the 4M distance as well.

Fig. A2. Relative calibration: Plot of the response measured from the PowerRefractor (y axis) as a function of the expected response (x axis). The slope and R^2 of the regression analysis are provided.

Fig. B1 (a) shows the comparison of phoria response obtained with CT and MTT. Figure B1 (b) shows a plot of the average phoria response obtained using the two methods vs. the difference between the two methods.

Fig. B2: Repeatability of MTT: Plot showing the average and mean differences in phoria determined using MTT on two separate sessions.

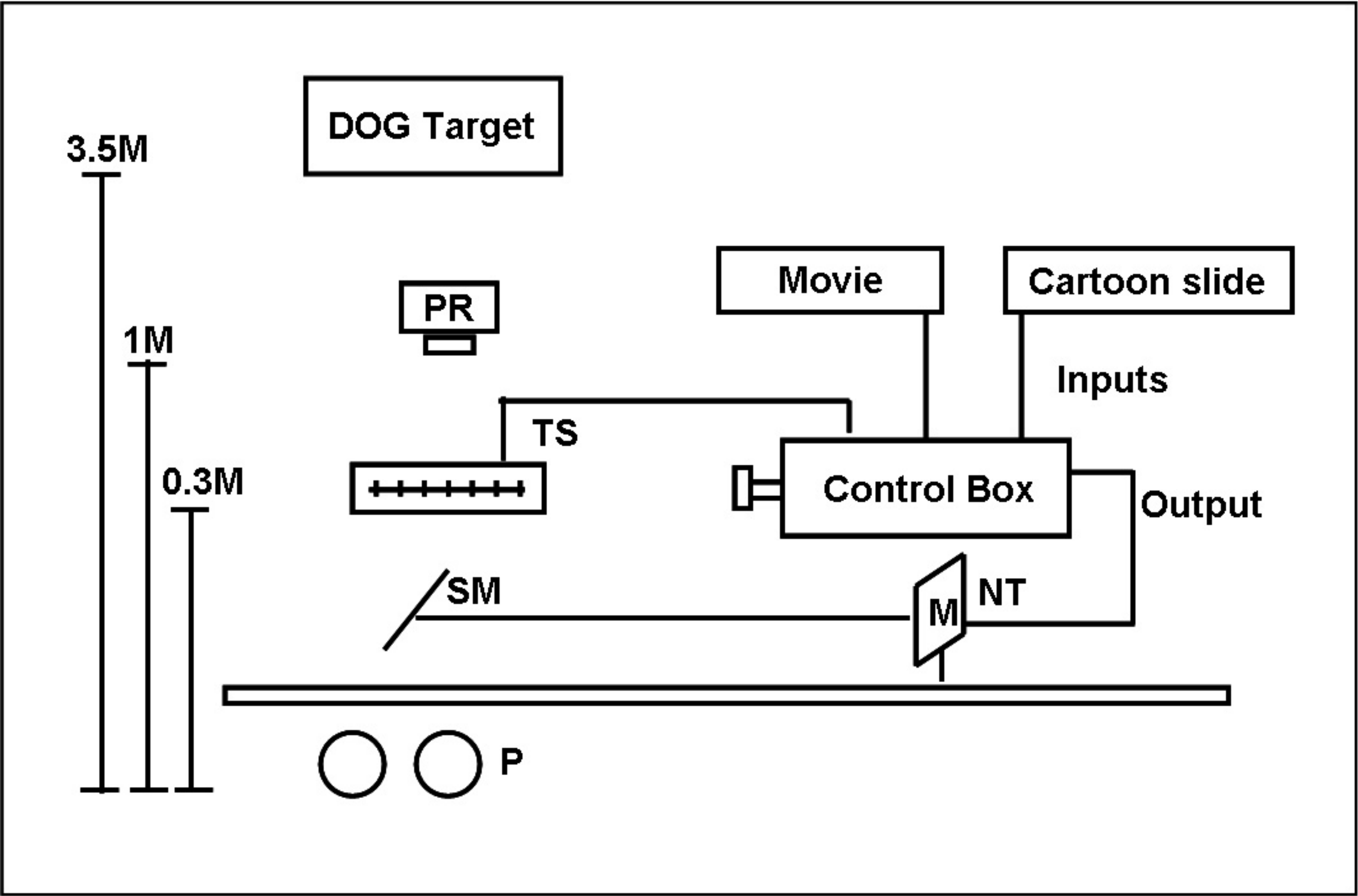
Table 1: Differences between binocular and monocular focuses at various time points with and without +2D lenses

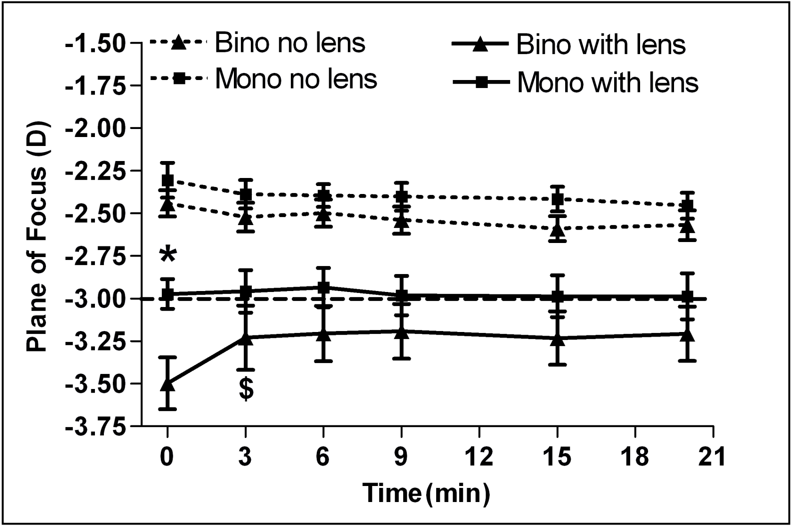
Time (mins)	**Mean differences between binocular and monocular focus (BF-MF) D**	
	No addition lens	**With +2D addition lens**
0	-0.12 ± 0.08	-0.50 ± 0.10 *****
3	-0.11 ± 0.07	-0.25 ± 0.15
6	-0.06 ± 0.07	-0.24 ± 0.12
9	-0.12 ± 0.06	-0.20 ± 0.13
15	-0.16 ± 0.07	-0.25 ± 0.12
20	-0.10 ± 0.06	-0.22 ± 0.13

* indicates P<0.05; Values indicate mean ± SE

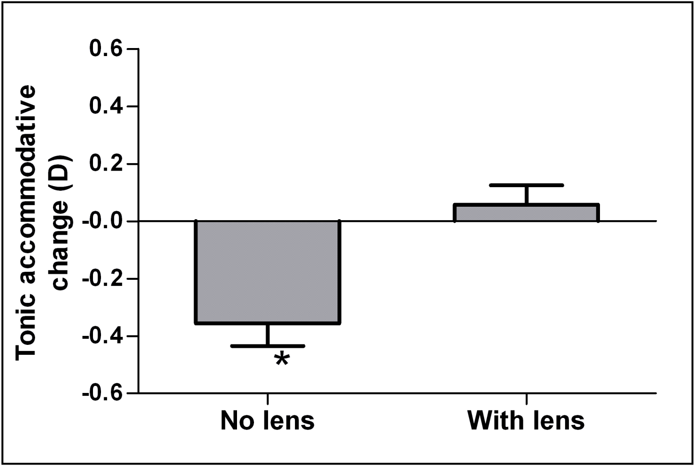
Table 2: Comparison of completeness of adaptation as a function of AV/A ratio in two studies

Investigator	**Percentage of completion**			
	Low St-AV/A (1.5-2.75 ∆D/D)		**High St-AV/A (3 -4∆D/D)**	
	3 – 3.5 min	**After 20 min**	**3 – 3.5 min**	**After 20 min**
Current study	71% (N =3)	89% (N = 3)	48% (N = 3)	74% (N =3)
North and Henson (1980)	55% (N = 1)	86% (N =1)	44% (N = 3)	65% (N = 3)

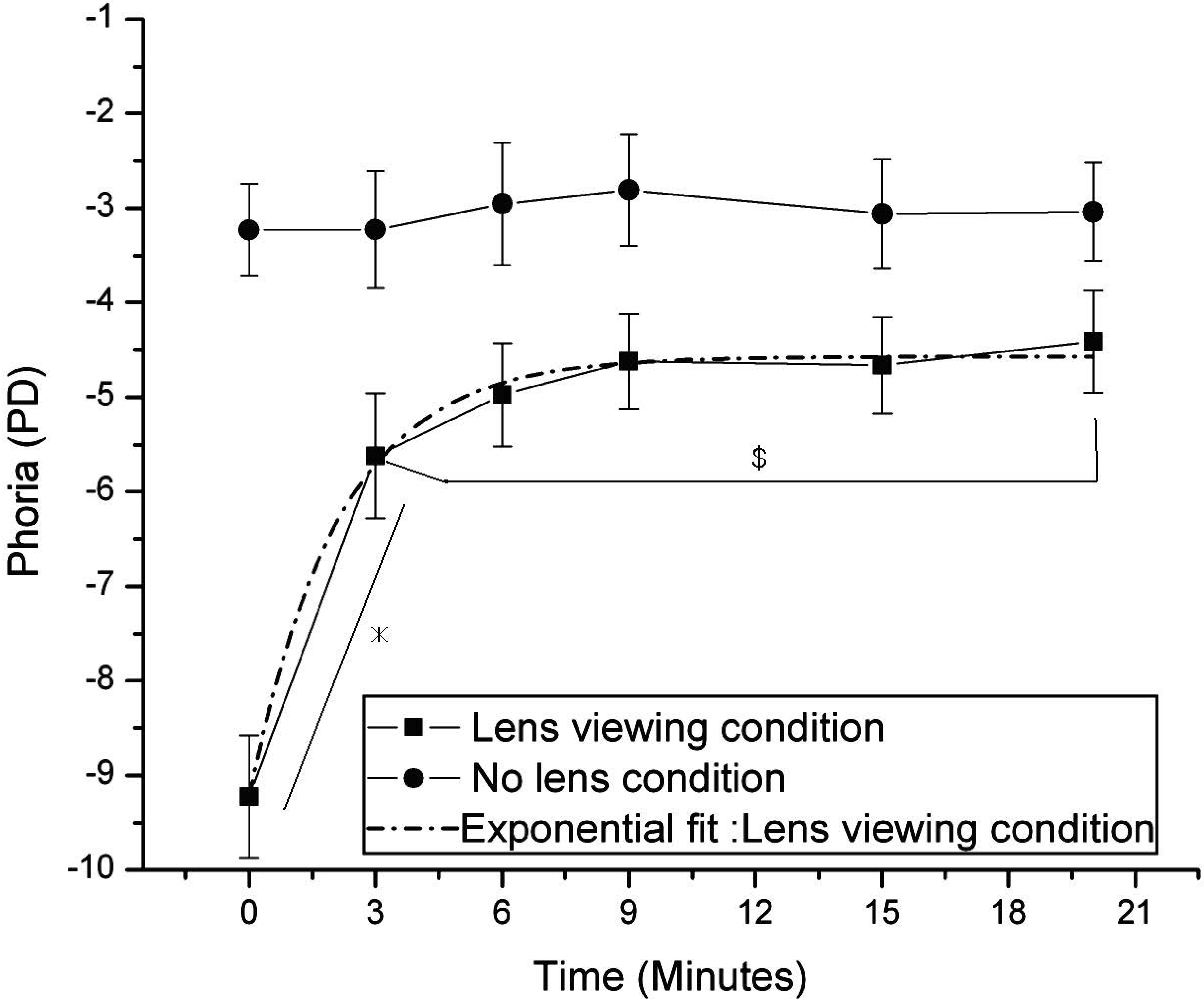

DOG Target
3.5M
1M
0.3M
PR
Movie
Cartoon slide
Inputs
TS
Control Box
Output
SM
M
NT
P



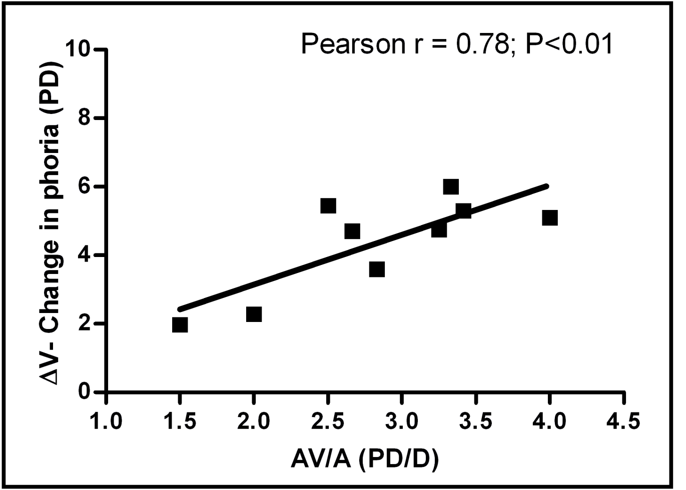
Bino no lens
Mono no lens
Bino with lens
Mono with lens
Plane of Focus (D)
-1.50
-1.75
-2.00
-2.25
-2.50
-2.75
-3.00
-3.25
-3.50
-3.75
*
$
0
3
6
9
12
15
18
21
Time (min)

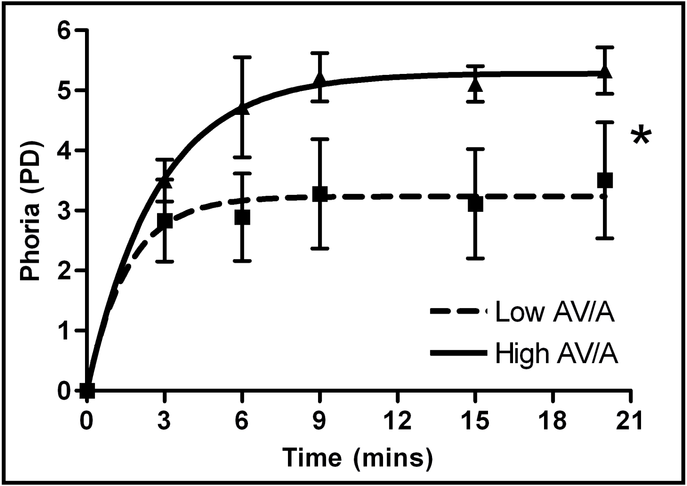


0.6
0.4
0.2
-0.0
-0.2
-0.4
-0.6
Tonic accommodative change (D)
*
No lens
With lens



Phoria (PD)
-1
-2
-3
-4
-5
-6
-7
-8
-9
-10
0
3
6
9
12
15
18
21
Time (Minutes)
$
*
Lens viewing condition
No lens condition
Exponential fit :Lens viewing condition


Pearson r = 0.78; P<0.01
ΔV- Change in phoria (PD)
AV/A (PD/D)
0
2
4
6
8
10
1.0
1.5
2.0
2.5
3.0
3.5
4.0
4.5



Phoria (PD)
0
1
2
3
4
5
6
*
Low AV/A
High AV/A
0
3
6
9
12
15
18
21
Time (mins)