Effect of heterophoria type and myopia on accommodative and vergence responses during sustained near activity in children

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Abstract

The influence of phoria-type and myopia on changes to vergence and accommodation during prolonged near-task was examined in 53 children. Participants were classified into phoria and refractive categories based on near phoria and cycloplegic refraction respectively. Measures of near phoria, binocular (BA) and monocular accommodation (MA) were obtained before and during a 20 min task when children binocularly fixated a high-contrast target at 33 cm through best corrective lenses. Vergence adaptation and accommodative adaptation were quantified using changes to near phoria and tonic accommodation respectively. The direction and magnitude of vergence adaptation was modified by the phoria-type ($p<0.001$). Emmetropic exophores displayed convergent (less exo than baseline) adaptation while esophores showed divergent shifts (less eso than baseline) in phoria upon prolonged fixation. Myopic children also followed a similar pattern but showed greater divergent (or less convergent) shift ($p<0.001$) in vergence adaptation for all phoria categories compared to emmetropes. Phoria-type also influenced the pattern of BA vs. MA ($p<0.001$) such that exophores showed BA>MA while esophores showed MA>BA in both refractive groups. Accommodative adaptation was higher in myopes ($p=0.010$) but did not demonstrate a significant effect of phoria ($p=0.4$). The influence of phoria-type on vergence adaptation and the pattern of BA vs. MA relates primarily to the varying fusional vergence demands created by the direction of phoria. The greater divergent (or less convergent) shift in vergence adaptation seen in myopes (compared to emmetropes) could be attributed to their higher accommodative adaptation. Nevertheless, the adaptive patterns observed in myopic children do not appear to explain their high response AV/A ratios identified as a risk factor for myopia development.

KEYWORDS: Near work, accommodation, vergence, myopia, adaptation

1. Introduction

1.1 Near work and the accommodation, vergence response

Near work requires the activation of the accommodation and vergence systems to achieve clear and single binocular vision. Numerous studies have shown that sustained near fixation induces adaptation of the accommodation and vergence systems (Ebenholtz, 1983; Ehrlich, 1987; Fisher et al., 1987; Gilmartin & Bullimore, 1991; Owens & Wolf-Kelly, 1987; Schor et al., 1984; Wolf et al., 1987; see { Rosenfield, 1997; Rosenfield et al., 1994 for review}). This adaptation has been attributed to the prolonged rate of decay of the slow controller of vergence/accommodation, which replaces the fast controller and exhibits a shift in the tonic levels of accommodation/ vergence (Schor, 1979a; 1979b). Accommodative adaptation is characterized by a post-task shift in the dark focus or tonic accommodation (Bullimore & Gilmartin, 1989; Ebenholtz, 1983; Fisher et al., 1987; Gilmartin & Bullimore, 1991; McBrien & Millodot, 1988). In the vergence system, past studies show convergent (eso) shifts in tonic vergence after a period of sustained near work (Ehrlich, 1987; Owens & Wolf-Kelly, 1987; Wolf et al., 1987).

1.2 Phoria and near task adaptation

Heterophoria (phoria) is a misalignment of the visual axes that occurs in the absence of fusion. This deviation is compensated during binocular viewing by fusional vergence. The degree and type of fusional vergence required for binocular viewing (convergence/divergence) varies directly with the size and direction of the phoria (exo/eso). The presence of exophoria necessitates an increase in fast fusional convergence while an esophoric deviation requires an increase in reflex fusional divergence to attain binocular single vision. Prolonged output of the fast fusional vergence (convergence/divergence) leads to vergence adaptation, which results in phoria changes in the direction of the elicited fusional vergence (Schor, 1979a) Thus, differing vergence postures (esophoria/exophoria) may produce asymmetries in phoria adaptation to a near-task (Ehrlich, 1987; Owens & Wolf-Kelly, 1987). Ehrlich (1987) measured changes to near phoria before and after a two hour near task at 20 cm in adult participants with mixed refractive errors. A mean convergent shift of 1.62Δ and a significant relationship between pre-task near phoria and vergence adaptation was reported. However, the sample only consisted of one esophore (others ranged from ortho to 16 exo). Also, only individuals with exophoria greater than 5Δ demonstrated a convergent shift similar to the mean (Fig 3 of the paper). Participants with low exo/ortho showed a divergent shift in phoria, which was not readily explained by their fusional demand. The author did not measure accommodative adaptation (changes to dark focus) but reported 0.29D change in distant refraction (transient myopia in closed loop accommodation) after the near task. Differences in accommodative adaptation, combined with varying strengths of accommodative-vergence cross-link may explain the divergent shift in vergence adaptation (Schor & Kotulak, 1986) seen in low exo/orthophores.

Most of the above-cited works on near task adaptation were performed in adults; relatively limited studies have measured adaptation in children (Gwiazda et al., 1995; Rosenfield et al., 1994; Wong et al., 2001; Woung et al., 1993). Wong et al (2001) compared vergence adaptation in children (mean age=9.8 years) and young adults (mean age=25.8 years) by measuring tonic vergence before and after a prolonged near task (reading at a distance of 15 cm for 5 minutes under closed loop accommodation and vergence). Children showed significantly greater vergence adaptation (0.45MA) compared to adults (0.11 MA). However, other ocular motor parameters like accommodative adaptation and AV/A ratio that may alter the vergence response and hence, its adaptation were not reported. Given that accommodation and vergence are tightly coupled systems, it is crucial to measure changes to both systems, especially when the adapting stimulus involves dual closed-loop conditions. To date, no study has measured adaptation of both accommodation and vergence in response to a sustained near task in children, and there is a paucity of information on the role of childhood phoria levels on this adaptation.

1.3 Myopia and adaptation to sustained near task in children

Numerous studies have identified refractive group differences in near work attributes. Myopic children show a reduced accommodative response especially under monocular viewing conditions (Berntsen et al., 2011; Gwiazda et al., 1993; Mutti et al., 2006) and full correction (Nakatsuka et al., 2005), increased variability of accommodation (Langaas et al., 2008; Sreenivasan et al., 2011), elevated response AV/A ratios (Gwiazda et al., 1999; Mutti et al., 2000), and recently, reduced fusional vergence ranges (Anderson et al., 2011). With regards to near-task induced adaptation, Gwiazda et al (1995) showed that myopic children exhibit greater accommodative adaptation to a near task compared to emmetropes. Since myopes demonstrate elevated response AV/A ratios (Gwiazda et al., 1999; Mutti, et al., 2000), even small differences in the accommodative system may produce larger changes in their vergence system compared to emmetropes.

Esophoria is associated with the onset or progression of myopia (Goss, 1990; Goss & Wolter, 1999) and with higher amounts of myopia (Chung & Chong, 2000). Goss and Rosenfield (1998) speculated that increased vergence adaptation to a prolonged near task may be a source for this convergent shift and thus a possible risk factor for myopic development/progression. However, to date, no study has measured vergence adaptation to a near task in myopic children with varying near phoria profiles. It may be possible that myopic children with different near phorias exhibit varying directions and magnitudes of phoria adaptation due to the alterations in fusional vergence demand. Further, if myopes show larger accommodative adaptation (Gwiazda et al., 1995; Woung et al., 1993), they may show reduced vergence adaptation, based on the reciprocal relation between the adaptive parameters observed in earlier reports (Schor 1988a; 1988b). Such adaptive behaviour may enhance the accommodative response and reduce the blur produced by excessive accommodative lags under binocular viewing conditions. To investigate the above mentioned hypothesis, this study evaluated the influence of phoria category (eso/exo/phoria normals) and myopia on near-task adaptation of vergence and accommodation following sustained binocular fixation at 33 cm through best corrective lenses.

2. Methods

2.1 Study participants

Fifty three children (28 myopic and 25 emmetropic; 58% female) between the ages of 7 and 15 years were recruited from the clinic database at the School of Optometry, University of Waterloo. Informed consent (parents) and assent (children) were obtained after verbal and written explanation of the nature of the study. The protocol followed the tenets of Declaration of Helsinki and received approval from the University of Waterloo ethics review board.

Participants with normal general and ocular health (determined from their clinical records and confirmed during a screening visit) underwent a preliminary examination to ensure the following: myopia between -0.75 and -6 D or *"emmetropia"* between +0.25 and +1.5 D, determined using cycloplegic refraction (two drops of 1% tropicamide added to both the eyes followed by retinoscopy and subjective refraction 20 min after the 2nd cycloplegic drop); astigmatism < 1D; anisometropia < 1D; best corrected visual acuity of at least 6/6 in each eye; non-strabismic; normal amplitudes of accommodation. Further, it was confirmed that participants were not taking any medications that might influence the accommodation and vergence systems. The range of refractive error in the "emmetropic group" was set to ensure that participants were clearly not myopic and therefore confirm distinct refractive differences between the study groups.

All children were classified into one of the three phoria categories based on their near phoria at 33 cm. Participants were classified as *"phoria normals"* if their near phorias were between 0-4 exo, *exophores* if phorias were >6 exo or *esophores* if phorias were >2 eso. Table 1 lists the critical visual parameters, including the number of children in each refractive and phoria category.

<INSERT TABLE 1>

2.2 Instrumentation

The overall study design involved prolonged binocular viewing through distance corrective lenses for 20 min with periodic measurements of phoria and accommodation, to quantify the time course of changes in either system. The instrumentation and procedure used for accommodation and phoria measurements were similar to previous studies (Sreenivasan et al., 2008; 2009).

2.2.1 Measurement of vergence adaptation and accommodation

Vergence adaptation was quantified by measuring changes in near phoria using the modified Thorington technique (MTT). This technique has been shown to be repeatable and valid in adults and in children (Casillas & Rosenfield, 2006; Rainey et al., 1998; Schroeder et al., 1996; Sreenivasan et al., 2008). Near phoria was measured at 33 cm using the modified Thorington technique and a tangent scale. The scale consisted of a small central aperture to accommodate the light source and a horizontal row of letters/numbers on either side. Children 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 to prevent fast fusional vergence and 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 measurement was repeated thrice and the near heterophoria was defined as the average of the three responses.

Accommodative responses were obtained immediately following the phoria measurement using the *monocular mode* of an eccentric infra-red (IR) photorefractor, the PowerRefractor (Multichannel Co, Reutlingen, Germany) (see Choi et al., 2000 for description). This setting of the instrument determined refraction along the vertical meridian of the participant's eye, sampling at a rate of 25 Hz, coupled with measures of gaze direction and pupillary diameter. Binocular accommodation (BA; accommodation was recorded from the right eye alone, although both eyes fixated at the target) and monocular accommodation (MA; left eye was briefly occluded for 5 sec) were recorded continuously for a period of 5sec after confirming steady fixation using the gaze control function displayed on the PowerRefractor interface. Additionally, care was taken to ensure that the child was fixating the near target at the correct fixation distance (33 cm) while measurements were recorded. A volunteer constantly monitored the head position of the child and ensured that it remained within the chin rest during measurement. If any unsteady fixation was noticed during measurement, or when the examiner observed off axis gaze errors exceeding 10 degrees, the measures were flagged using keyboard inputs and discarded given the possibility of under or over estimation of accommodation (Ferree et al., 1931; Millodot & Lamont, 1974). In these cases, recordings were obtained for an additional 5 sec period to ensure equal size data sets across subjects.

A high contrast colour cartoon (contrast =85%; target luminance =15 cd/m^2) provided the stimulus to accommodation in children. This target was used elsewhere (Sreenivasan et al., 2009) and found to be more successful than conventional reading material in holding the participant's attention while proving to be an effective stimulus for accommodation (Sreenivasan et al., 2008). The image of the cartoon was displayed on a 1.77″ wide liquid crystal display monitor (Model No: LT-V18 U; Victor company of Japan) and projected at a distance of 33cm through a semi-silvered mirror. The mirror set 10 cm from the right eye, and angled at 45 degrees allowed the photorefractor to simultaneously record accommodation from the right eye during target viewing. The method has been described in detail elsewhere (Sreenivasan et al., 2008).

The responses obtained from the PowerRefractor were calibrated using a two-step protocol to ensure relative and absolute accuracy of accommodation similar to previous studies (Blade & Candy, 2006; Sreenivasan et al., 2008; Sreenivasan et al., 2009). While the slope of the calibration function matched with the instruments default for some participants, others needed separate calibration functions, possibly due to differences in fundal reflectance (Howland, 2009; Schaeffel et al., 1993). In all cases, accommodative responses were calibrated based on calibration equations for each individual.

2.3 Experimental procedure

Prior to the start of the study session, participants sat in total darkness for 3 minutes to dissipate any effects of previous near work and to allow the accommodation and vergence system to return to their resting states (Wolf et al., 1987). Pre-task measures of tonic accommodation were then taken when participants monocularly fixated a 0.2 cpd difference of Gaussian target at 4 metres in an otherwise dark room. Baseline measures of phoria, BA and MA were then taken at 33 cm prior to the sustained near fixation through best corrective lenses. The time required for one complete measurement block (measurement of phoria, binocular and monocular accommodation) ranged between 60 and 80 sec. Care was taken to ensure that measures fell within this time frame in order that the adaptation design was consistent.

Near task: The “sustaining target” was a cartoon movie, played at a distance of 33 cm. This target has also been used in previous studies (Sreenivasan et al., 2008; 2009) and was chosen to avoid boredom and ensure prolonged near fixation for the scheduled duration of the study (20 min). Measures of phoria, BA and MA were repeated after 2, 4, 6, 8, 10, 15 and 20 min to determine the time course of changes in accommodation and vergence. Immediately after completion of the near task (within 30-40 sec) tonic accommodation was recorded to facilitate the estimation of accommodative adaptation.

2.4 Data Analysis

Measurement of the accommodative response at 25 Hz for 5 sec provided a total of 125 data points. Each data point was accepted based on criteria similar to previous studies (Sreenivasan et al., 2008; 2009; 2011). Data from one myopic participant was excluded from the averaging process since she failed to provide the minimum levels of acceptable data as a result of pupil diameters less than 4mm.

Repeated measures analysis of variance (ANOVA) was used to compare the mean changes in accommodation and phoria with sustained fixation. In all cases, statistically significant main effects were further examined using Tukey Honestly significant differences (HSD) post-hoc tests. Differences were considered statistically significant when the likelihood of a type-I error was <0.05. Data analysis was performed using STATISTICA 6.0 (StatSoft, Inc, USA). Exponential curve fitting analysis was performed using Graphpad software (Graphpad Inc, USA) to compare the absolute magnitude and time course for the adaptation in different groups. Pearson correlations were performed to look for relationships between phoria, accommodative response and near-task adaptation.

3. Results

3.1 Time course of changes to near phoria during sustained binocular fixation

The mean baseline phoria for each phoria-type and refractive category is provided in Table 1. Analysis of variance comparing the baseline phorias between the various groups showed that each category of phoria differed significantly from the others in both refractive groups (i.e. Phoria normals vs. esophores vs. exophores: $p<0.001$). However, the baseline near phoria for a given phoria-category was not significantly different between myopes and emmetropes (Main effect of refractive type on baseline phoria: $p=0.84$: Post-hoc p values: MN vs EN =0.94; MEvs EE=0.26; MX vs EX=0.18). Figs 1 (a, b and c) show the time course of changes to near phoria during 20 minutes of sustained fixation with respect to each phoria-category in the two refractive groups. In the exo category (Fig 1a), both emmetropes (EX) and myopes (MX) showed significant reduction of exo (i.e. convergent adaptation, $p=0.03$) after 4 min of near fixation; however EX showed greater ($p<0.01$) shifts compared to MX. In the phoria normal category, emmetropes (Fig 1b) showed a small and significant reduction in exophoria (convergent shift) ($p=0.010$) that saturated following 2 min of fixation. While the myopic phoria-normals seemed to follow a similar pattern in the initial 2 min (Fig 1b), their phoria responses showed a small but significant divergent shift (increased exo) after 20 min of sustained fixation (time point 0 vs.20 min: $p=0.010$). Both esophoric groups (EE&ME; Fig 1c) showed reduction of esophoria (i.e., divergent adaptation), which differs in direction compared to exophores and phoria normals. Sustained fixation in EE and ME resulted in a significant divergent adaptation (ME: $P<0.001$; EE: $p=0.05$) with greater adaptation in ME compared to EE ($p=0.04$).

<INSERT FIGS (1a, b and c) HERE>

The overall effect of phoria-category and myopia on the magnitude of vergence adaptation to a near task was analyzed by computing total adaptation (i.e., change in phoria after 20 min) from each participant using an exponential function. Statistical analysis showed a significant main effect of phoria-category ($p<0.001$) and refractive type ($p<0.001$) on total adaptation but non-significant interaction between the two factors ($p=0.80$). Further, baseline near phoria and the total magnitude of vergence adaptation were significantly correlated for both refractive groups (Fig 2; Emm; $r^2=0.37$; $r= -0.61$; $p=0.001$; Myo; $r^2=0.47$; $r= -0.69$; $p<0.001$) such that exophores showed convergent adaptation compared to a divergent adaptation in esophores. Linear regression analysis showed similar slopes for the two refractive groups (Emm= -0.30 ± 0.08; Myo= -0.21 ± 0.04; $p=0.34$) but significantly divergent intercept in myopes (Emm=0.20 ± 0.34; Myo=-1.15 ± 0.27; $p<0.001$) compared to emmetropes.

<INSERT FIG 2 HERE>

3.2 Changes to binocular (BA) and monocular accommodative (MA) response

3.2.1 Pattern of BA vs. MA in the different phoria-categories

Fig 3 shows the mean binocular and monocular accommodative responses for each phoria-category averaged from the first time point (0 min) in all children (irrespective of their refractive classification). Binocular accommodation differed significantly ($p=0.003$) across phoria-categories but, the monocular measures remained similar between the groups ($p=0.90$). While BA is significantly greater than MA in exophores ($p<0.001$) and phoria normals ($p=0.030$), BA is significantly attenuated ($p=0.003$) compared to MA in esophores. Furthermore, the lag of the accommodative response varied as a function of phoria-category in the binocular viewing condition such that exophores displayed significantly less lags of accommodation compared to esophoric children ($p=0.020$).

<INSERT FIG 3 HERE>

The effect of phoria on the difference between binocular and monocular accommodative response (attributed to the output of vergence accommodation) was quantified using the Pearson correlation coefficient. Both refractive groups showed significant correlation between the two variables (Fig 4: Emm; $r^2=0.54$; $r= -0.74$; $p<0.001$; Myo; $r^2=0.49$; $r= -0.69$; $p<0.001$) such that exophores showed higher binocular accommodation (and more convergence accommodation) compared to esophores. Linear regression analysis of the two variables showed similar slopes (Emm= -0.04; Myo= -0.03; $p=0.32$) and intercept (Emm=0.007; Myo=0.01; $p=0.87$) for both refractive groups, suggesting similar VA/V ratios in the two refractive groups.

<INSERT FIG 4 HERE>

Refractive type showed a significant main effect ($p=0.010$) such that myopes displayed greater accommodative lags compared to emmetropes (Fig 5, time 0). However, interaction between phoria and refractive error was non-significant ($p=0.60$) such that the pattern of BA vs. MA remained similar in myopes in each phoria-category but only shifted the overall response towards increased accommodative lag (Fig 4).

<INSERT FIG 5 HERE>

3.2.2 Time course of changes to accommodation during sustained binocular fixation

The type of phoria (Exo/Eso) continued to show a significant effect (P<0.0001) on the pattern of BA vs. MA over time (Fig 5) such that exophores displayed larger BA while esophores exhibited higher MA, similar to pre-near task. During the prolonged near task, all myopic phoria groups showed a small but significant increase (0.2-0.3D) in accommodative response (all p<0.05) after 4 min of near fixation. Emmetropic children also showed similar small (0.15-0.3D) but significant changes after 6 min of viewing. The changes in accommodative response over time for each phoria and refractive category were fit with an exponential function to compare the magnitude of change in closed-loop accommodation and its time constant between groups. The total magnitude of change in accommodation did not show any significant effect of refractive type (Myo =0.28±0.05D; Emm= 0.22±0.04D; p=0.50), type of phoria (Exo=0.16±0.06D; Eso=0.27±0.05D; PN=0.21 ± 0.05D; p=0.60) or viewing condition (Bino=0.24±0.05D; Mono=0.21±0.03D; p=0.80). Similarly, the time constant (ranged between 4-6 min) did not show any significant difference (all p<0.50) between the type of phoria and refractive group in this study sample. It is important to note that accommodation was not adapted monocularly since the prolonged viewing was performed under binocular viewing conditions.

3.3 Changes to open-loop accommodative response

Accommodative adaptation was defined as the difference between pre and post TA measures. All phoria categories in each refractive type showed significant myopic shift in TA (all p<0.05) after the near task (Fig 6). While myopes showed higher accommodative adaptation compared to emmetropes (p=0.010), the magnitude of accommodative adaptation did not differ between the phoria categories in each refractive group (p=0.40) and interaction between phoria-category and refractive type was also not significant (p=0.99).

<INSERT FIG 6 HERE>

4. Discussion

4.1 Effect of phoria-category and myopia on vergence adaptation

Our results indicate that vergence adaptation to a sustained near task does not shift in a convergent direction in all children. The type of near phoria and presence of myopia influences the magnitude and direction of vergence adaptation to a near task. In both refractive groups, exophores showed a convergent shift while esophores showed a divergent shift in near phoria. These differences are consistent with the models of vergence (Schor, 1979b) wherein vergence adaptation is dependent upon the magnitude and direction of reflex fusional vergence. The presence of exophoria necessitates an increase in fusional convergence (resulting in a convergent vergence adaptation) while an esophoric deviation requires an increase in fusional divergence (resulting in a divergent vergence adaptation) in order to attain binocular single vision. The greater the baseline phoria, the greater the amount of fusional vergence required to overcome the phoria, resulting in greater amounts of vergence adaptation (Fig 2). This also explains why small baseline phorias in phoria-normals have little adaptation response (Fig 2). This relationship between phoria-category (esophoria/exophoria) and adaptation to a near-task is consistent with previous studies (Ehrlich, 1987; Owens & Wolf-Kelly, 1987). Nevertheless, it should also be noted that few other studies report no significant relationship between baseline phoria and adaptation (North & Henson., 1981; Kim et al., 2010). Of these, one study measured prism adaptation in esophoric and exophoric participants with abnormal binocular vision or asthenopia (North & Henson., 1981) and in the other study, the majority of the participants were exophoric (two participants with esophoria=2PD; Kim et al., 2010) Thus differences in these studies can likely be attributed to attenuated adaptive processes found in individuals with binocular anomalies (North & Henson., 1981) in the former case and a lack of full spectrum of vergence-bias in the latter (Kim et al., 2010).

This is the first study to show an influence of myopia on vergence adaptation to near task in the various phoria categories. For all types of phoria, myopic children show a greater divergent (or less convergent) shift in vergence adaptation compared to emmetropes. Although vergence adaptation was primarily attributed to the sustained effort of fusional vergence similar to emmetropes, one possible explanation for less convergent shift in myopes could be related to the increased tonic accommodative after effects observed in these children (Fig 6 and Gwiazda et al., 1995). Accommodative adaptation may reduce the output of the accommodative vergence cross-link, resulting in an exophoric or divergent shift (Schor & Kotulak, 1986; Schor, 1986). This suggestion is consistent with previous studies that show an exo (divergent) shift in phoria due to accommodative adaptation (Jiang, 1996), similar to the reduction in VA cross-link activity with vergence adaptation (Schor & Kotulak, 1986; Schor & Tsuetaki, 1987; Sreenivasan et al., 2009). Furthermore, the divergent shift due to accommodative adaptation may be greater in myopes compared to emmetropes due to the higher AV/A ratio seen in myopic children (Gwiazda et al., 1999; Mutti et al., 2000). Nevertheless, the adaptive behaviour observed in myopes (more divergent vergence adaptation and higher accommodative adaptation) may enhance the accommodative response and reduce the blur produced by excessive accommodative lags.

It has been suggested that near esophoria is associated with the development (Goss, 1991) and increased rates of myopic progression (Chung & Chong, 2000). Goss and Rosenfield (1998) speculated that vergence adaptation to a near task may be a source for this esophoria. The authors suggested that this esophoria may then cause increased accommodative lags under binocular condition, inducing hyperopic retinal defocus that may result in axial elongation (Irving et al., 1992; Schaeffel et al., 1988; Smith III et al., 1994). In the current study, phoria-normals and exophores showed a convergent shift in vergence adaptation after sustained near task. But, esophores, especially the myopes showed greater divergent adaptation (exophoric shift) with sustained fixation. If esophoria produced by vergence adaptation to a near task is a risk factor for the progression of myopia (Goss & Rosenfield, 1998), then phoria normals/exophores may be susceptible to the development/progression of myopia. Based on the same hypothesis, near esophoric profile does not appear to be crucial in the development or progression of myopia since their baseline esophoria reduced with prolonged binocular fixation.

4.2 Effect of phoria category and myopia on accommodative adaptation

Sustained fixation of the near task increased the tonic accommodative levels in both myopic and emmetropic children, but myopes showed significantly greater accommodative adaptation to the near task compared to emmetropes. This is consistent with previous studies that measured the shift in tonic accommodation in myopic children (Gwiazda et al., 1995) and late onset myopes (Woung et al., 1993), but not with adults who had been early onset myopes (McBrien & Millodot, 1988). The difference could be related to the duration of myopia since children and adults with recent onset show greater shifts than individuals with long-term myopia (Gwiazda et al., 1995). The larger shifts in myopic children are also consistent with reports that show greater NITM (near work induced transient myopia) in myopic children (Wolffsohn et al., 2003), where again, the myopic (tonic) shift represents the output of the slow component of the accommodative response.

Phoria-type showed non-significant effects on accommodative adaptation, despite the small differences observed between the groups (Fig 6). Past research suggests that accommodative adaptation is the result of prolonged rate of decay of the slow accommodative controller, which receives input from the phasic controller and the convergence accommodation cross-link (Schor, 1986; Schor & Kotulak, 1986). In this study, a stimulus at 33 cm produced similar monocular blur-driven accommodative response, suggestive of a similar phasic component (see Fig 3 monocular response at time point 0) in all phoria groups. Under binocular conditions, the contribution of vergence accommodation cross-link (VA) was different between the phoria-categories, such that exophores provided a larger output from convergence accommodation compared to esophores (Fig 3). With sustained fixation, the groups showed vergence adaptation (Fig 1 a, b), which is expected to alter the VA cross-link activity (Schor & Tsuetaki, 1987; Sreenivasan et al., 2009) and possibly reduced the differences observed between the groups.

4.3 Pattern of binocular vs. monocular accommodative response with the type of phoria

Another key finding of this study is the reversal of the binocular vs. monocular accommodative response in children with exophoria and esophoria in both refractive groups. Heterophoria is overcome by fusional vergence, which in addition to maintaining single vision, also alters the binocular accommodative response through the VA/V cross-link. Accordingly, the differences between binocular and monocular viewing conditions observed in the vergence categories can be attributed to the activation of vergence accommodation. Exophores employ increased convergence to maintain bifoveal fixation, which enhances convergence accommodation such that binocular measures are greater than monocular levels. On the other hand, esophores exert fusional divergence to maintain single vision, which results in a reduced output of vergence accommodation and greater monocular compared to binocular accommodation. The findings of this study are consistent with the model predictions (Schor, 1999) that propose changes to binocular accommodation (BA) alone with changes in phoria. The monocular accommodative response (MA) remained unaffected, presumably due to the absence of vergence accommodation input. The relationship between the binocular accommodative response and phoria seen in this study is consistent with clinical observations (Evans & Pickwell, 2007; Scheiman & Wick, 2008) and previous reports from retrospective (Tassinari, 2002) and prospective studies (Goss & Rainey, 1999; Hasebe et al., 2005). However, the current study also measured monocular accommodation, which confirms that the differences seen in binocular viewing conditions were related to near phoria and thus, the fusional vergence demand and vergence accommodation. The difference between binocular vs. monocular accommodation have important clinical implications for the diagnosis and treatment of convergence insufficiency and convergence excess. Traditionally, tests such as dynamic retinoscopy and monocular estimation method attest to the measurement of accommodation under binocular viewing conditions (Scheiman & Wick, 2008), which would show larger lags in esophores and more accurate accommodation response in exophores. These responses are seen clinically (Evans & Pickwell, 2007; Scheiman & Wick, 2008) and are predicted from clinical models that do not directly consider vergence accommodation. The present results emphasize the role of vergence accommodation in the binocular accommodative response.

The presence of myopia did not alter the pattern of binocular vs. monocular accommodative response but resulted in larger lags in all phoria groups under both binocular and monocular conditions. While previous studies showed larger accommodative lags in myopic children under monocular viewing conditions (Gwiazda et al., 1993; Mutti et al., 2006), this was not seen when both eyes observed the target (Rosenfield & Desai, 2002; Seidel et al., 2005). It is important to note that latter studies that showed no refractive group differences under binocular viewing conditions did not differentiate their participants based on phoria-category. Our results show that phoria-category does not influence the monocular accommodation response for the range tested. Previously, Gwiazda et al (1999) showed a moderate correlation (their Fig 3b; $r = -0.35$; $P=0.040$) between near phoria and monocular accommodation in myopes but not emmetropes. Visual inspection of their data shows similar accommodative responses across most phoria magnitudes except for a few myopic children with extremely high eso and exophoria ($\pm 15\Delta$). Several studies have recorded monocular accommodation in an attempt to study the contribution of phoria. For instance, studies that measured the effect of progressive addition lenses in reducing myopic progression measured monocular accommodation and quantified the effect of monocular lags in different phoria groups (Gwiazda et al., 2004; Hasebe et al., 2008). Based on the results of this study, it appears that studies including participants with a wide range of phoria should include the measurement of both monocular and binocular accommodation, as the latter incorporates the fusional vergence response (and vergence accommodation) to overcome phoria.

4.4 Adaptation- Implications for myopia development

Accommodative adaptation was higher and vergence adaptation was less convergent in myopes compared to emmetropes. Based on previous studies (Schor, 1988a; Schor & Horner, 1989) and the model of accommodation and vergence (Schor, 1992), these adaptive parameters would result in low AV/A ratios and high VA/V ratios. However, myopic children in this study had relatively high AV/A ratios and similar VA/V ratios respectively compared to emmetropes (Table 1). Thus, the cross links findings in myopes are not readily explained from these models and the interactions of phasic and adaptive responses (Schor, 1992). It is evident that the etiology of the increased AV/A in myopes requires other variables perhaps not unlike those which define an independent gain regulation of the AV (and VA) ratio (Miles et al., 1987). Higher response AV/A ratios have been found to be elevated in those children (Gwiazda et al., 1999; Mutti et al., 2000) and adults (Jiang, 1995) who became myopic and identified as a possible risk factor for myopia development. The results of this study indicate that adaptive parameters of accommodation/vergence are not the likely cause for such behaviour.

Another possibility for high AV/A ratios in myopes may be related to sensory factors. A few reports have indicated that myopes' exhibit reduced sensory perception or an increased threshold for blur compared to emmetropes (Jiang, 1997; Rosenfield & Abraham-Cohen, 1999). Reduced blur sensitivity has been modelled as an increased depth of focus in infant studies (Green et al., 1980). Models of accommodation unanimously place depth of focus element prior to the accommodative controller (Hung & Semmlow, 1980; Jiang, 1999; Schor, 1992). A large depth of focus would certainly reduce accommodation (and increase accommodative lags) but it should also reduce not increase accommodative vergence as observed in myopes. The most parsimonious explanation at this point would be that the accommodative plant of the myopic eye (lens, ciliary body and zonules) requires greater levels of accommodation to effect a given dioptric change in comparison to an emmetropic eye, similar to the pseudocycloplegia hypothesis proposed by Mutti and colleagues (2000). This increased innervation would lead to the high AV/A due to increased accommodative effort, which may then lead to the high accommodative lag. Accommodative lag may then be a resultant of the properties of the myopic eye and not a causative factor for the development of myopia.

In conclusion, the present study has identified differences in adaptive behaviour of young myopes vs. emmetropes to a sustained near task. These adaptive patterns do not appear to explain their high response AV/A ratios, that has been previously identified as a risk factor for myopia development. Nevertheless, it is important to note that this was a cross-sectional study performed on myopic children. It may be beneficial to longitudinally evaluate the role of adaptive parameters in children prior to the development of myopia.

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References

Anderson, H., Stuebing, K. K., Fern, K. D., & Manny, R. E. (2011). Ten-year changes in fusional vergence, phoria, and nearpoint of convergence in myopic children. Optometry & Vision Science, 88, 1060-1065

~~Banks, M. S., Green, D. G., & Powers, M. K. (1980). Depth of focus, eye size and visual acuity. Vision Research, 20, 827-835.~~

Berntsen, D. A., Sinnott, L. T., Mutti, D. O., & Zadnik, K. (2011). Accommodative lag and juvenile-onset myopia progression in children wearing refractive correction. Vision Research, 51; 1039-46

Blade, P. J., & Candy, T. R. (2006). Validation of the PowerRefractor for measuring human infant refraction. Optometry and Vision Science, 83, 346-353.

Bullimore, M. A., & Gilmartin, B. (1989). The measurement of adaptation of tonic accommodation under two open-loop conditions. Ophthalmic and Physiological Optics, 9, 72-75.

Casillas Casillas, E., & Rosenfield, M. (2006). Comparison of subjective heterophoria testing with a phoropter and trial frame. Optometry and Vision Science, 83, 237-241.

Choi, M., Weiss, S., Schaeffel, F., Seidemann, A., Howland, H. C., Wilhelm, B., & Wilhelm, H. (2000). Laboratory, clinical, and kindergarten test of a new eccentric infrared photorefractor (PowerRefractor). Optometry and Vision Science, 77, 537-548.

Chung, K. M., & Chong, E. (2000). Near esophoria is associated with high myopia. Clinical & Experimental Optometry, 83, 71-75.

Ebenholtz, S. M. (1983). Accommodative hysteresis: A precursor for induced myopia? Investigative Ophthalmology & Visual Science, 24, 513-515.

Ehrlich, D. L. (1987). Near vision stress: Vergence adaptation and accommodative fatigue. Ophthalmic & Physiological Optics, 7, 353-357.

Evans, B. J. W., & Pickwell, D. (2007). Pickwell's binocular vision anomalies: Investigation and treatment. Fifth ed. Butterworth-Heinemann, Oxford

Ferree, C. E., Rand, G., & Hardy, C. (1931). Refraction for the peripheral field of vision. Archives of Ophthalmology, 5, 717-731.

Fisher, S. K., Ciuffreda, K. J., & Levine, S. (1987). Tonic accommodation, accommodative hysteresis, and refractive error. American Journal of Optometry and Physiological Optics, 64, 799-809.

Gilmartin, B., & Bullimore, M. A. (1991). Adaptation of tonic accommodation to sustained visual tasks in emmetropia and late-onset myopia. Optometry & Vision Science, 68, 22-26.

Goss, D. A., & Rosenfield, M. (1998). Vergence and myopia, in Rosenfield, M & Gilmartin. B(eds.), Myopia and Nearwork, Butterworth-Heinemann, pp. 147–161.

Goss, D. A. (1991). Clinical accommodation and heterophoria findings preceding juvenile onset of myopia. Optometry and Vision Science, 68, 110-116.

Goss, D. A. (1990). Variables related to the rate of childhood myopia progression. Optometry and Vision Science, 67, 631-636.

Goss, D. A., & Rainey, B. B. (1999). Relationship of accommodative response and nearpoint phoria in a sample of myopic children. Optometry and Vision Science, 76, 292-294.

Goss, D. A., & Wolter, K. L. (1999). Nearpoint phoria changes associated with the cessation of childhood myopia progression. Journal of the American Optometric Association, 70, 764-768.

Green, D. G., Powers, M. K., & Banks, M. S. (1980). Depth of focus, eye size and visual acuity. Vision Research, 20, 827-835.

Gwiazda, J., Bauer, J., Thorn, F., & Held, R. (1995). Shifts in tonic accommodation after near work are related to refractive errors in children. Ophthalmic & Physiological Optics, 15, 93-97.

Gwiazda, J., Grice, K., & Thorn, F. (1999). Response AC/A ratios are elevated in myopic children. Ophthalmic & Physiological Optics, 19, 173-179.

Gwiazda, J., Thorn, F., Bauer, J., & Held, R. (1993). Myopic children show insufficient accommodative response to blur. Investigative Ophthalmology & Visual Science, 34, 690-694.

Gwiazda, J. E., Hyman, L., Norton, T. T., Hussein, M. E., Marsh-Tootle, W., Manny, R., Wang, Y., & Everett, D. (2004). Accommodation and related risk factors associated with myopia progression and their interaction with treatment in COMET children. Investigative Ophthalmology & Visual Science, 45, 2143-2151.

Hasebe, S., Nonaka, F., & Ohtsuki, H. (2005). Accuracy of accommodation in heterophoric patients: Testing an interaction model in a large clinical sample. Ophthalmic and Physiological Optics, 25, 582-591.

Hasebe, S., Ohtsuki, H., Nonaka, T., Nakatsuka, C., Miyata, M., Hamasaki, I., & Kimura, S. (2008). Effect of progressive addition lenses on myopia progression in Japanese children: A prospective, randomized, double-masked, crossover trial. Investigative Ophthalmology & Visual Science, 49, 2781-2789.

Howland, H. C. (2009). Photorefraction of eyes: History and future prospects. Optometry and Vision Science, 86, 603-606.

Hung, G. K., & Semmlow, J. L. (1980). Static behavior of accommodation and vergence: Computer simulation of an interactive dual-feedback system. IEEE Transactions on Bio-Medical Engineering, 27, 439-447.

Irving, E. L., Sivak, J. G., & Callender, M. G. (1992). Refractive plasticity of the developing chick eye. Ophthalmic & Physiological Optics, 12, 448-456.

Jiang, B. C. (1997). Integration of a sensory component into the accommodation model reveals differences between emmetropia and late-onset myopia. Investigative Ophthalmology & Visual Science, 38, 1511-1516.

Jiang, B. C. (1996). Accommodative vergence is driven by the phasic component of the accommodative controller. Vision Research, 36, 97-102.

Jiang, B. C. (1999). A modified control model for steady-state accommodation. In: H. Franzen, H. Richter & L. Stark (Eds.), Accommodation and vergence mechanisms in the visual system, Texas: Birkhauser pp. 1-11.

Jiang, B. C. (1995). Parameters of accommodative and vergence systems and the development of late-onset myopia. Investigative Ophthalmology and Visual Science, 36, 1737-1742.

Kim, E. H., Granger-Donetti., B, Vicci., V. R, Alvarez, T. L. (2010) The relationship between phoria and the ratio of convergence peak velocity to divergence peak velocity. Investigative Ophthalmology & Visual Science, 51, 4017-4027.

Langaas, T., Riddell, P. M., Svarverud, E., Ystenaes, A. E., Langeggen, I., & Bruenech, J. R. (2008). Variability of the accommodation response in early onset myopia. Optometry and Vision Science, 85, 37-48.

McBrien, N. A., & Millodot, M. (1988). Differences in adaptation of tonic accommodation with refractive state. Investigative Ophthalmology & Visual Science, 29, 460-469.

Millodot, M., & Lamont, A. (1974). Letter: Refraction of the periphery of the eye. Journal of the Optical Society of America, 64, 110-111.

Mutti, D. O., Mitchell, G. L., Hayes, J. R., Jones, L. A., Moeschberger, M. L., Cotter, S. A., Kleinstein, R. N., Manny, R. E., Twelker, J. D., & Zadnik, K. (2006). Accommodative lag before and after the onset of myopia. Investigative Ophthalmology & Visual Science, 47, 837-846.

Miles, F. A., Judge, S. J., & Optician, L. M., (1987). Optically-induced changes in the couplings between vergence and accommodation. The Journal of Neuroscience, 7, 2576-2589

Mutti, D. O., Jones, L. A., Moeschberger, M. L., & Zadnik, K. (2000). AC/A ratio, age, and refractive error in children. Investigative Ophthalmology Visual Science, 41, 2469-2478.

Nakatsuka, C., Hasebe, S., Nonaka, F., & Ohtsuki, H. (2005). Accommodative lag under habitual seeing conditions: Comparison between myopic and emmetropic children. Japanese Journal of Ophthalmology, 49, 189-194.

North,R., & Henson, D.B. (1981). Adaptation to prism-induced heterophoria in subjects with abnormal binocular vision or asthenopia. American Journal of Optometry and Physiological Optics,58, 746-52.

Owens, D. A., & Wolf-Kelly, K. (1987). Near work, visual fatigue, and variations of oculomotor tonus. Investigative Ophthalmology & Visual Science, 28, 743-749.

Rainey, B. B., Schroeder, T. L., Goss, D. A., & Grosvenor, T. P. (1998). Inter-examiner repeatability of heterophoria tests. Optometry and Vision Science, 75, 719-726.

Rosenfield, M., Chiu, N. N., Ciuffreda, K. J., & Duckman, R. H. (1994). Accommodative adaptation in children. Optometry & Vision Science, 71, 246-249

Rosenfield, M., & Desai, R. (2002). Do progressing myopes show reduced accommodative responses? Optometry & Vision Science, 79, 268-273

Rosenfield, M. (1997). Tonic vergence and vergence adaptation. Optometry and Vision Science, 74, 303-328.

Rosenfield, M., & Abraham-Cohen, J. A. (1999). Blur sensitivity in myopes. Optometry and Vision Science, 76, 303-307.

Rosenfield, M., Ciuffreda, K. J., Hung, G. K., & Gilmartin, B. (1994). Tonic accommodation: A review II. accommodative adaptation and clinical aspects. Ophthalmic and Physiological Optics, 14, 265-277.

Schaeffel, F., Glasser, A., & Howland, H. C. (1988). Accommodation, refractive error and eye growth in chickens. Vision Research, 28, 639-657.

Schaeffel, F., Wilhelm, H., & Zrenner, E. (1993). Inter-individual variability in the dynamics of natural accommodation in humans: Relation to age and refractive errors. The Journal of Physiology, 461, 301-320.

Scheiman, M., & Wick, B. (2008). Clinical management of binocular vision: Heterophoric, accommodative, and eye movement disorders. Lippincott Williams & Wilkins, Philadelphia.

Schor, C. (1999). The influence of interactions between accommodation and convergence on the lag of accommodation. Ophthalmic & Physiological Optics, 19, 134-150.

Schor, C. (1988a). Imbalanced adaptation of accommodation and vergence produces opposite extremes of the AC/A and CA/C ratios. American Journal of Optometry and Physiological Optics, 65, 341-348.

Schor, C. (1988b). Influence of accommodative and vergence adaptation on binocular motor disorders. American Journal of Optometry & Physiological Optics, 65, 464-475.

Schor, C., & Horner, D. (1989). Adaptive disorders of accommodation and vergence in binocular dysfunction. Ophthalmic & Physiological Optics, 9, 264-268.

Schor, C. M. (1992). A dynamic model of cross-coupling between accommodation and convergence: Simulations of step and frequency responses. Optometry and Vision Science, 69, 258-269.

Schor, C. M. (1986). The Glenn A. Fry award lecture: Adaptive regulation of accommodative vergence and vergence accommodation. American Journal of Optometry & Physiological Optics, 63, 587-609.

Schor, C. M. (1979a). The influence of rapid prism adaptation upon fixation disparity. Vision Research, 19, 757-765.

Schor, C. M. (1979b). The relationship between fusional vergence eye movements and fixation disparity. Vision Research, 19, 1359-1367.

Schor, C. M., Johnson, C. A., & Post, R. B. (1984). Adaptation of tonic accommodation. Ophthalmic & Physiological Optics, 4, 133-137.

Schor, C. M., & Kotulak, J. C. (1986). Dynamic interactions between accommodation and convergence are velocity sensitive. Vision Research, 26, 927-942.

Schor, C. M., Kotulak, J. C., & Tsuetaki, T. (1986). Adaptation of tonic accommodation reduces accommodative lag and is marked in darkness. Investigative Ophthalmology and Visual Science, 27, 820-827.

Schor, C. M., & Tsuetaki, T. K. (1987). Fatigue of accommodation and vergence modifies their mutual interactions. Investigative Ophthalmology & Visual Science, 28, 1250-1259.

Schroeder, T. L., Rainey, B. B., Goss, D. A., & Grosvenor, T. P. (1996). Reliability of and comparisons among methods of measuring dissociated phoria. Optometry and Vision Science, 73, 389-397.

Seidel, D., Gray, L. S., & Heron, G. (2005). The effect of monocular and binocular viewing on the accommodation response to real targets in emmetropia and myopia. Optometry and Vision Science, 82, 279-285.

Smith III, E. L., Li-Fang, H., & Harwerth, R. S. (1994). Effects of optically induced blur on the refractive status of young monkeys. Vision Research, 34, 293-301.

Sreenivasan, V., Irving, E. L., & Bobier, W. R. (2011). Effect of near adds on the variability of accommodative response in myopic children. Ophthalmic and Physiological Optics, 31, 145-154.

Sreenivasan, V., Bobier, W. R., Irving, E. L., & Lakshminarayanan, V. (2009). Effect of vergence adaptation on convergence-accommodation: Model simulations. IEEE Transactions on Bio-Medical Engineering, 56, 2389-2395.

Sreenivasan, V., Irving, E. L., & Bobier, W. R. (2009). Binocular adaptation to +2 D lenses in myopic and emmetropic children. Optometry and Vision Science, 86, 731-40

Sreenivasan, V., Irving, E. L., & Bobier, W. R. (2008). Binocular adaptation to near addition lenses in emmetropic adults. Vision Research, 48, 1262-1269.

Tassinari, J. T. (2002). Monocular estimate method retinoscopy: Central tendency measures and relationship to refractive status and heterophoria. Optometry & Vision Science, 79, 708-714.

Wolf, K. S., Ciuffreda, K. J., & Jacobs, S. E. (1987). Time course and decay of effects of near work on tonic accommodation and tonic vergence. Ophthalmic & Physiological Optics, 7, 131-135.

Wolffsohn, J. S., Gilmartin, B., Li, R. W., Edwards, M. H., Chat, S. W., Lew, J. K., & Yu, B. S. (2003). Nearwork-induced transient myopia in preadolescent Hong-Kong Chinese. Investigative Ophthalmology Visual Science, 44, 2284-2289.

Wong, L. C., Rosenfield, M., & Wong, N. N. (2001). Vergence adaptation in children and its clinical significance. Binocular Vision & Strabismus Quarterly, 16, 29-34.

Woung, L. C., Ukai, K., Tsuchiya, K., & Ishikawa, S. (1993). Accommodative adaptation and age of onset of myopia. Ophthalmic and Physiological Optics, 13, 366-370.