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Accommodation functions: Co-dependency and relationship to refractive error

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Abstract

We assessed the extent to which different accommodative functions are correlated and whether accommodative functions predict the refractive error or the progression of myopia over a 12 month period in 64 young adults (30 myopes and 34 non-myopes). The functions were: amplitude of accommodation; monocular and binocular accommodative facility (6 m and 40 cm); monocular and binocular accommodative response to target distance; AC/*A* and CA/*C* ratios, tonic accommodation (dark focus and pinhole), accommodative hysteresis, and nearwork-induced transient myopia. Within groups of related accommodative functions (such as facility measures or open-loop measures) measurements on individuals were generally significantly correlated, however correlations between functions from different groups were generally not significant. Although accommodative amplitude and pinhole (open loop) accommodation were significantly different in myopes than in non-myopes, these functions were unrelated to myopia progression. Facility of accommodation and accommodative lag was independent predictors of myopia progression.

Keywords: Accommodation; Myopia; Refractive error

1. Introduction

There is strong evidence that the development of myopia in humans is influenced by both genetic makeup and environmental factors. Up to 80% of the variation in refractive error in humans may be explained by genetic factors (Hammond, Snieder, Gilbert, & Spector, 2001), and the number of myopic parents significantly increases the odds of children becoming myopic (Pacella et al., 1999). Evidence of environmental influence comes from a rapid increase in the prevalence of myopia in certain populations (Lam et al., 1994; Young et al., 1969) or in certain sub-groups of the population (McBrien & Adams, 1997; Zylbermann, Landau, & Berson, 1993), as well as an association of myopia with nearwork (Mutti, Mitchell, Moeschberger, Jones, & Zadnik, 2002). However, the relative importance of genetic makeup and environmental factors is still a matter of controversy (Gilmartin, 2004; Morgan & Rose, 2005).

Although the association between myopia and nearwork is long established (Angle & Wissmann, 1980; Richler & Bear, 1980; Zadnik, Satariano, Mutti, Sholtz, & Adams, 1994), the mechanism linking the two has not been confirmed, although accommodation malfunctions have been implicated.

The search for accommodative problems associated with myopia has resulted in some inconsistencies in the literature. For example, amplitude of accommodation has been found variously to be reduced in myopes (Duang, 1985; Fong, 1997; Zhai & Guan, 1988), increased in myopes (Fledelius, 1981; Maddock, Millodot, Leat, & Johnson, 1981; McBrien & Millodot, 1986a), and unaffected by the refractive error (Fisher, Ciuffreda, & Levine, 1987; Gawron, 1981; Mantyjarvi, 1987; Wold, 1967). Again, although a reduced accommodative

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response is found in myopes (Abbott, Schmid, & Strang, 1998; Gwiazda, Thorn, Bauer, & Held, 1993), there is some controversy about whether responses worsen as myopia progresses (Gwiazda, Bauer, Thorn, & Held, 1995a) or whether there is no relationship between progression and accommodative response (Rosenfield, Desai, & Portello, 2002).

Accommodative dynamics, assessed by facility of accommodation measurements are reduced for distance viewing in myopes (O'Leary & Allen, 2001), but not for nearwork (Jiang & White, 1999; O'Leary & Allen, 2001). The accommodative convergence to accommodation ratio may also be related to myopia (Gwiazda, Grice, & Thorn, 1999; Jiang, 1995; Mutti, Jones, Moeschberger, & Zadnik, 2000; Rosenfield & Gilmartin, 1987), however one study found no significant difference in the AC/*A* ratio between progressing myopes, stable myopes, and emmetropes (Chen et al., 2003).

Open-loop measures of accommodation, including tonic accommodation (Gwiazda, Bauer, Thorn, & Held, 1995b; Jiang, 1995; Yap, Garner, Kinnear, & Firth, 1998; Zadnik et al., 1999), accommodative hysteresis (Gwiazda et al., 1995b; McBrien & Millodot, 1988; Woung, Ukai, Tsuchiya, & Ishikawa, 1993), and a slower regression to baseline levels (Gilmartin & Bullimore, 1991; Hazel, Strang, & Vera-Diaz, 2003; Strang, Winn, & Gilmartin, 1994) have also been associated with myopia. Other transient effects associated with myopia are nearwork-induced transient myopia and the post-task decay rate (Ciuffreda & Lee, 2002; Ciuffreda & Wallis, 1998; Hazel et al., 2003; Vera-Diaz, Strang, & Winn, 2002; Wolffsohn et al., 2003).

A lag of accommodation could provide a stimulus to myopisation (Gwiazda et al., 1993) analogous to the hypermetropic defocus model that is known to induce myopia in animals (Diether & Schaeffel, 1997; Hung, Crawford, & Smith, 1995; Smith, 1998; Smith & Hung, 1999). One might expect that a near addition in myopia would reduce progression. Although results have not been conclusive across all myopes, Progressive Addition Lenses significantly reduce progression over a 3 year period in children with larger lags of accommodation in combination with near esophoria and shorter reading distances (Gwiazda et al., 2003, 2004), supporting the accommodative lag hypothesis. However, Chung, Mohidin, and O'Leary (2002) suggested that the presence of blurred vision at any distance may stimulate the progression of myopia regardless of the sign of defocus.

Studies associating accommodation anomalies with the presence, age of onset or progression of myopia have generally relied on retrospective data to establish progression or have not examined the broad spectrum of accommodative functions found to be anomalous, but have concentrated on only a few functions. It is not clear whether myopes classified as progressing from retrospective data were continuing to progress at the time the accommodation functions were established. In addition, it is not clear whether the various accommodation anomalies are independently linked to myopia progression or whether they are correlated.

The main aim of this study was to examine whether accommodative anomalies are related to: the refractive error, the age of onset of myopia or the progression of myopia over a period of 12 months. We measured a wide range of accommodative functions in myopes and non-myopes to determine if differences exist between the refractive error groups. We also examined the correlation between accommodative functions to assess the extent to which they are co-dependent. Finally, we used a multiple regression model to see if any of the accommodative functions influence the progression of myopia.

2. Methods

2.1. Participants

Sixty-four participants (30 males, 34 females) in good ocular and systemic health took part in the study. The participants were students attending Anglia Polytechnic University, Cambridge campus. The mean age was 20.14 ± 1.55 years (range 18–22 years). Additional inclusion criteria were: at least 6/6 (20/20) corrected visual acuity in both eyes; no more than 1.00 D astigmatism in either eye; normal ocular motility and near point of convergence (less than 8 cm); good stereopsis (40″) with no history of orthoptic treatment or patching. The maximum anisometropia present was 0.75 D and no case was antimetropic.

Refractive error was classified with cycloplegia on the basis of the mean of a series of 3 Nidek AR-600A autorefractor readings from the Left Eye. (Two drops of cyclopentolate hydrochloride 1% (Minims; Chauvin), the second drop being instilled 5 min after the first, were used to obtain complete cycloplegia as many of the participants were of Asian origin.) To facilitate classification, the autorefractor readings were converted to equivalent spherical values (sphere plus half the cylinder). No subject had a change from non-myopic to a myopic classification because of the cylinder power.

Thirty myopes (refractive error $\geqslant -0.25$ D) and 34 non-myopes (plano < refractive error $\leqslant +1.00$ D) enrolled on the study. The myopes were further subdivided into early-onset ($n = 18$) and late-onset myopes ($n = 12$) (Goldschmidt, 1968; Goss & Winkler, 1983). The early-onset myopes were subjects who first began spectacle wear before they were 15 years and the late-onset myopes began spectacle wear after their 15th birthday.

Informed consent was obtained from every subject after both a verbal and a written explanation of the procedures and possible consequences were given. The tenets of the Declaration of Helsinki were followed. The research had the approval of Anglia Polytechnic University Research Ethics Committee.

2.2. Accommodative functions

Accommodative functions previously reported as being linked to myopia were included in the study; that is, amplitude of accommodation; accommodative facility; accommodative response amplitude; accommodative convergence to accommodation (AC/A) ratio; convergent accommodation to convergence (CA/C) ratio; tonic accommodation; accommodative hysteresis; nearwork-induced transient myopia. We intended to measure both accommodation response curves to targets at different distances and also responses to negative lenses; our protocols for these measures required that where a participant had an accommodative error of greater than 2.00 D to any negative lens stimulus, the stimulus should be reapplied after the participant was told that focussing was inaccurate. Unfortunately in many cases the process was repeated several times until the accommodative response improved, often substantially. The result was that some participants with initially poor accommodative response amplitudes to negative lenses effectively had significant amounts of accommodative training before readings were recorded. We are therefore unable to give data of all participants' responses to negative lenses under identical experimental conditions, and so have not included these data in the results and analysis.

The order in which accommodation functions were measured was randomised apart from the accommodative facility measurements, which were measured last.

2.2.1. Amplitude of accommodation

A modified RAF near point rule (Clement Clarke Ltd.) was used to measure amplitude of accommodation. To minimise the overestimation of the amplitude of accommodation caused by the change in retinal image size as the target approaches the subject (Somers & Ford, 1983) a target was constructed consisting of a photographically reduced chart (Atchison, Capper, & McCabe, 1994a, 1994b). Letters were arranged in words with six words on each line. The sizes of letters were chosen so that at each 0.5 D step (from 2.5 to 7.5 D) the subject would be viewing a line of words consisting of letters with an acuity value of 1′. For amplitudes of 7.5 D or greater the smallest letters were more suitable than that of the larger N5 print on the standard RAF near point rule as they were closer to the threshold letter size, but the use of letters larger than 1′ might lead to a slight overestimation of the amplitude in participants with over 8.0 D accommodation.

Measurements were taken from the left eye only with the right eye occluded with a patch. Spectacles were worn when the measurements were taken. The vertex distance was assessed using a vertex distance gauge and the interpupillary distance measured with a corneal reflex pupillometer, so that ocular accommodation could be calculated. The RAF rule was angled slightly down (Atchison et al., 1994a, Atchison, Claydon, & Irwin, 1994b; Ripple, 1952); and was illuminated by an incandescent lamp. The subject was initially instructed to focus and read the top line of print placed at 40 cm (2.5 D). The examiner moved the target inward in discrete half dioptre steps with the subject reading words from one line down each step. As the target was advanced, the examiner continuously adjusted the position of the lamp to keep the lamp–target distance constant. The luminance level was maintained at approximately 20 cd/m^2. After each step the subject was requested to 'try very hard to keep the words on the appropriate line perfectly clear and to report when this is not possible'. When the amplitude was 7.5 D or higher the smallest line was used as the target.

2.2.2. Accommodative facility

Accommodative facility was investigated at both 6 and 0.4 m, monocularly (left eye only) and binocularly in a random order. A suppression check was included for the binocular measurements (Burge, 1979). Participants were allowed approximately 20 s of practice prior to the first test to ensure that they understood the test procedures.

2.2.2.1. Monocular distance accommodative facility test. Monocular accommodative facility in the distance was measured using a −2.00 D lens, with the subject viewing 6/9 letters placed 6 m away. The chart was internally illuminated and the room lights were on. The right eye was occluded with a patch.

The participants were instructed as follows:

You should look at the letters and try to keep them clear. I am going to put a lens in front of your eye and the letters will blur for a short time and then become clear again. As soon as they are clear again please say 'clear'. I will then remove the lens and the letters might be blurred again; say 'clear' as soon as you can see the letters clearly again. I will go on repeating this procedure to see how often you can clear the lens in a 1-min period.

2.2.2.2. Binocular distance accommodative facility test. Binocular accommodative facility in the distance was measured for 6/9 letters using a pair of mounted −2.00 D lenses. The lenses had polarisers attached. Two cross-polarised red lines on the target (subtending 10′) formed the suppression test. The position of the red lines was demonstrated without the lenses in place. The lenses (and polarisers) were then placed in front of the eyes and a check that both red strips were seen (the top red strip was seen by the left eye and the lower strip by the right eye) was performed. This was a fairly gross suppression check but had the advantage of keeping the complexity of the task relatively simple.

The instruction set was similar to before with the addition of "Do not say clear unless the letters are single and both the red lines are visible".

2.2.2.3. Monocular near accommodative facility test. Monocular accommodative facility was measured at 0.4 m. The targets were high contrast 6/9 letters, in a test unit which was mounted on a stand. The chart was internally illuminated, the room lights were on, and an angle poise lamp provided additional local illumination. The instruction set was similar to the distance instructions, except this time two lenses (one +2.00 D, the other −2.00 D, mounted on a flipper bar) were interchanged. The test always began with the +2.00 D lens.

2.2.2.4. Binocular near accommodative facility test. Binocular accommodative facility at near was measured using ±2.00 D lenses mounted on a flipper. The instruction set was similar to the binocular distance instructions, except this time two lenses (one +2.00 D, the other −2.00 D, mounted on a flipper bar) were interchanged.

An audio tape recording of the participants' responses was used to record results for later analysis. The participants said 'clear' when the target became clear. In addition to accommodative facility values, the responses were split into positive response time (time to accommodate through the negative lenses) and negative response time (time to relax accommodation either through the positive lenses or when the negative lenses are removed).

The protocols for measuring accommodative facility in this study are very similar to those used in many previous studies of clinical facility measurements. The results include the reaction and response times of the observer and experimenter to the stimulus clearing, and thus the positive and negative response times derived from facility measurements are longer than those gained from objective optometers.

2.2.3. Accommodative response amplitude

Accommodative response amplitudes were determined using a PowerRefractor (MultiChannel Systems) eccentric photorefractor (Choi et al., 2000). The data were obtained from the left eye.

During some measurements a Kodak Wratten 87C filter (Wratten filter) was used to occlude the vision in one eye. This filter transmits infrared light but not visible light, allowing the PowerRefractor to obtain a reading. When a pinhole lens was required a 0.5-mm hole was manually drilled into a Kodak Wratten 87C filter (Pinhole Wratten filter) allowing the PowerRefractor to obtain a measurement from the full pupil while vision was through a pinhole.

2.2.3.1. Calibration. To achieve optimal measurement precision during the study the PowerRefractor was calibrated for each subject individually due to large variations in calibrations among subjects (Choi et al., 2000; Gekeler, Schaeffel, Howland, & Wattam-Bell, 1997; Hunt, Wolffsohn, & Gilmartin, 2003; Schaeffel, Weiss, & Seidel, 1999; Seidemann & Schaeffel, 2003).

For calibration the left eye was occluded with a Wratten filter while the right eye fixated a 6/9 letter placed at 6 m. During fixation with the right eye, trial lenses (+4.00 to −1.00 DS) were placed in front of the Wratten filter which was occluding the left eye. Measured refraction was compared to the refraction expected from the trial lenses, with allowances made for a vertex distance of 12 mm. The correction factor was taken from the slope and intercept of the linear regression trendline, and incorporated into any PowerRefractor measurements from that subject.

2.2.3.2. Accommodative response amplitude to a real target. The subject was positioned in a chin rest and brow bar 1 m distant from the PowerRefractor. During the monocular measurements the left eye was occluded with a Wratten filter while the right eye viewed the targets. During the binocular response amplitude measurement, both eyes viewed the target while the measurement was taken from the left eye.

The targets consisted of a row of letters. The angular subtense of the target detail at the eye was 1.5′ at the fixation distance. The fixation distances were 6, 3, 1, 0.5, 0.4, and 0.33 m, and were selected in a randomised order. The targets were positioned directly in front of the subject with the PowerRefractor displaced very slightly from the line of sight. Participants were instructed to keep the letters clear at all times and to inform the examiner if this was not possible (Stark & Atchison, 1994). For each accommodative demand a continuous measurement for 10 s was taken and the average was calculated. When a data set on a subject was complete, linear regression was performed and the response amplitude at different stimulus levels was extrapolated. These response amplitudes were used to calculate any leads or lags (MLAG and BLAG) of accommodation. The slope and intercept of the least squares linear fit from each subject were used.

A method to compare accommodation stimulus–response curves is the accommodative error index (AEI) (Chauhan & Charman, 1995). The AEI for the monocular response to targets placed at different distances was calculated using the following formula (Chauhan & Charman, 1995):

$$\mathrm{AEI} = \frac{(1-m)[(x_1+x_2)/2]-c}{r^2},$$

where m is the slope of the response line, c the intercept of the response line, x_1 the dioptric equivalent of the farthest stimulus, x_2 the dioptric equivalent of the nearest stimulus, and r is the correlation coefficient.

2.2.4. Accommodative convergence to accommodation (AC/A) ratio

The PowerRefractor was used in combination with a Bernell Muscle Imbalance Measure (MIM) test card placed at 0.4 m from the spectacle plane of the participants. The PowerRefractor was used to measure the accommodative response amplitude in the left eye, which was occluded with a Wratten filter, while the right eye viewed the numbers on the MIM card (approximately 20′) through the appropriate lenses. The habitual correction was worn. Measurements (for 10 s) were taken with the following lenses: +1.00, −1.00, +2.00, and −2.00 D in that order.

The MIM card was then used, with a central penlight, to measure the induced heterophoria. The left eye viewed the MIM card and penlight through a Maddox rod while trial lenses (+1.00, −1.00, +2.00, and −2.00 D) were placed in front of the right eye. The overall convergence was calculated by subtracting (if exophoria) or adding (if esophoria) the reading from the MIM card from the near convergence demand for each subject. The near convergence demand was calculated by dividing the interpupillary distance in centimetres by the target distance in metres. The response AC/*A* ratios were obtained by calculating the slope of the principal axis (Sokal & Rohlf, 1969).

2.2.5. Stimulus convergent accommodation to convergence (CA/C) ratio

The accommodation loop was opened using 0.5-mm pinholes (Ward & Charman, 1987). The participants viewed binocularly 6/9 letters through 0.5-mm Pinhole Wratten filters at a viewing distance of 0.5 m. The pinhole lenses were placed before each eye and subjectively aligned by alternative occlusion in order to ensure binocular viewing of the letters. Convergence was changed by the introduction of 6 Δ[1] base-in, 12 Δ[1] base-in, 2 Δ[1] base-out, 6 Δ[1] base-out, and 12 Δ[1] base-out prisms in front of the right eye. A plano prism lens was inserted for the baseline reading. Participants were instructed to concentrate on a specific letter and to 'relax your eyes but keep the letter single and say if the letter becomes double'. The accommodative response amplitude of the left eye was measured with the PowerRefractor, for 10 s.

2.2.6. Tonic accommodation

All the measurements in the following experiments were performed in the same laboratory minimising the effects of surround propinquity (Chiu & Rosenfield, 1994; Rosenfield & Gilmartin, 1990). Initially, seated at the PowerRefractor, subjects sat in darkness for 10 min to minimise any effects of previous nearwork (Krumholz, Fox, & Ciuffreda, 1986). The participants were then positioned in a chin and forehead rest and a baseline refractive error reading of the left eye was obtained using a 6/9 letter at 6 m as the fixation target. The two open-loop accommodation conditions were presented to each subject in random order.

2.2.7. Dark focus of accommodation

The room was darkened and the subject was asked to look straight ahead and to 'clear your mind'. This was to prevent any influence of mental activity on the level of tonic accommodation (Malmstrom & Randle, 1976). No readings were taken for 2 min in order to allow the level of tonic accommodation to stabilise (Rosenfield, Ciuffreda, Hung, & Gilmartin, 1993). A continuous reading of the refractive error of the left eye was then taken for 10 s. The score for dark focus accommodation was the mean value of this reading subtracted from the baseline reading.

2.2.8. Pinhole accommodation

Participants viewed a 6/9 letter at 6 m, through a Pinhole Wratten filter, placed 12 mm from the corneal apex in front of the left eye. The filter was mounted in a trial lens holder and placed in a trial frame. The right eye was occluded with an eye patch.

As with the dark focus accommodation measurement, no readings were taken for 2 min after the pinhole was positioned in front of the pupil of the left eye. A continuous reading for 10 s was then taken. The value for pinhole accommodation was the mean value of this reading subtracted from the baseline reading.

2.2.9. Accommodative hysteresis

Participants were positioned in a chin and forehead rest and a baseline refractive error reading of the left eye was obtained using a 6/9 letter at 6 m as the fixation target. Dark focus accommodation was measured as above. The nearwork task consisted of reading text (N10) from a paperback copy of 'Harry Potter and the Philosopher's Stone' placed at a distance of 20 cm. After 90 min of reading participants were then repositioned into the chin and forehead rest and the room placed in darkness again. This process took up to 20 s. A continuous reading of the refractive error of the left eye was taken for 10 s. The value for the post-task dark focus accommodation was the mean value of this reading subtracted from the baseline reading.

2.2.10. Nearwork-induced transient myopia

To obtain a baseline reading of the far-point a continuous reading of the refractive error of the left eye was taken for 10 s with participants fixating a 6/9

[1] Prism Dioptre symbol, Greek capital delta.

letter at 6 m. The nearwork task above was repeated and participants were positioned into the chin and forehead rest. A continuous reading of the refractive error of the left eye was taken for 10 s with the subject fixating a 6/9 letter at 6 m.

2.2.11. Refraction

The refractive error was determined by cycloplegic (two drops of cyclopentolate hydrochloride 1%) objective measurement with a Nidek AR600-A autorefractor using a series of 3 readings. A further series of 3 Nidek cycloplegic autorefractor readings was obtained 12 months later to determine any change in refractive error. The refractive errors were reported as mean spherical equivalents (sphere plus half the cylinder). The Nidek AR600-A has been shown to have excellent repeatability and validity (Allen, Radhakrishnan, & O'Leary, 2003). The Nidek autorefractor was used as no PowerRefractor readings could be obtained from the participants under cycloplegia due to very large pupil diameters.

In reporting changes in refractive error we included the net change between baseline and the 12 month follow up without removing changes which were clinically too small to warrant a change in prescription. This is because the changes measured are the best estimate we have of the refractive shift, and removing the small changes would effectively have classified them as zero, thus biasing the correlations with accommodative functions. The inclusion of these small changes in our regression model does not imply they are clinically important.

2.2.12. Statistical methods

The data set was first analysed cross-sectionally and then longitudinally in separate analyses. All data reported here were normally distributed according to the Kolmogorov–Smirnov test unless reported otherwise. Independent sample two-tailed t tests were used to determine whether the accommodation function was different between myopes and emmetropes. Next, to determine whether the accommodation functions varied between early-onset myopes, late-onset myopes, and non-myopes one-way between-groups analyses of variance were calculated. Post hoc analysis was performed using the Games–Howell test. Pearson's product–moment correlation coefficients were calculated when the correlation between the accommodation function and either refractive error or myopia progression was required. Multiple regression was used to select statistically significant explanatory variables for myopia progression. Initially univariate correlations of the accommodation functions, with the dependent variable being the progression of myopia, were determined. All correlations at $p < 0.25$ were considered for multiple regression.

3. Results

The cycloplegic refractive error ranged from −0.25 to −2.00 D (mean: −1.07 ± 0.62 D) in the late-onset myopic group; from −0.37 to −8.87 D (mean: −4.13 ± 2.35 D) in the early-onset myopic group, and between 0.00 and +1.00 D (mean: +0.57 ± 0.25 D) in the non-myopic group.

The mean accommodation functions for all participants are summarised in Table 1. The statistically significant correlations between different accommodative functions are given in Table 2 (all other correlations between accommodative functions are non-significant, and so have been omitted from the table).

Significant correlations are divided into three groups: facility measures, accommodative response amplitude measures, and adaptive measures. Most significant correlations lie within groups rather than between-groups. In addition, amplitude of accommodation and CA/*C* ratio are not assigned to a group, but show significant correlations with another measure.

The correlations between open-loop accommodative measures (pinhole vs dark focus) confirm earlier findings (Leibowitz & Owens, 1975a, 1975b), as does a correlation between hysteresis and near-induced transient myopia (Ong & Ciuffreda, 1995). Correlations between different measures of accommodative response amplitude are also not unexpected, as the error index is calculated from the average response amplitude data. Most measures of positive response time were significantly correlated, whilst generally measures of negative response time were not significantly correlated.

On average, myopes have significantly lower amplitude of accommodation, lower pinhole accommodation, and lower distance accommodative facility than non-myopes.

There also appears to be a significant relationship between the amount of myopia and the amplitude of accommodation, pinhole accommodation, and binocular lag of accommodation (Figs. 1A–C).

The only significant difference we found between early-onset and late-onset myopes was in the near monocular facility positive response time.

3.1. Myopia progression

A myopic shift in refractive error over the 12 month follow-up period was found in 58% (37/64) of participants, whereas 42% (27/64) had no change in refractive error. No subject showed a hypermetropic shift. The mean change in refractive error in those showing a myopic shift was −0.43 ± 0.34 D. Eight late-onset myopes (66%) exhibited a mean myopia progression of −0.45 ± 0.20 D; 14 early-onset myopes (77%) exhibited a mean myopia progression of −0.45 ± 0.34 D, and 15 non-myopes (44%) became myopic with a mean myopic shift of

Table 1
The mean accommodation functions for myopes and non-myopes where: AF is the accommodative facility, PRT is the positive response time, NRT is the negative response time, AEI is the accommodative error index, AH is the accommodative hysteresis, and NITM is the nearwork-induced transient myopia

	Distance monocular facility			Distance binocular facility		
	AF (cycles/min)	PRT (s)	NRT (s)	AF (cycles/min)	PRT (s)	NRT (s)
Emmetropes	18.54 ± 5.40	1.77 ± 0.81	1.46 ± 0.95	12.93 ± 7.33	3.14 ± 14.13	1.48 ± 1.30
Myopes	15.95 ± 4.91	2.17 ± 1.08	1.58 ± 0.67	11.05 ± 6.59	3.98 ± 15.62	1.39 ± 0.48
Significance (*t* test)	$p = 0.04^*$	$p = 0.04^*$	$p = 0.40$	$p = 0.29$	$p = 0.52$	$p = 0.68$
Late-onset myopes	13.83 ± 4.51	2.45 ± 1.29	1.88 ± 0.90	9.50 ± 7.63	4.66 ± 17.54	1.59 ± 0.49
Early-onset myopes	17.36 ± 4.76	2.03 ± 1.27	1.42 ± 0.32	12.08 ± 5.79	3.65 ± 14.28	1.29 ± 0.43
Significance (ANOVA)	$p = 0.05$	$p = 0.14$	$p = 0.90$	$p = 0.36$	$p = 0.49$	$p = 0.62$
	Near monocular facility			Near binocular facility		
Emmetropes	13.69 ± 5.93	1.86 ± 0.96	2.51 ± 3.29	10.03 ± 6.19	3.02 ± 4.90	3.03 ± 13.70
Myopes	12.62 ± 5.07	2.53 ± 3.21	2.15 ± 1.18	9.00 ± 5.76	4.02 ± 7.16	2.63 ± 10.55
Significance (*t* test)	$p = 0.44$	$p = 0.02^*$	$p = 0.09$	$p = 0.50$	$p = 0.15$	$p = 0.43$
Late-onset myopes	10.21 ± 5.80	3.32 ± 4.51	2.57 ± 1.53	7.63 ± 5.02	4.85 ± 8.74	3.10 ± 1.98
Early-onset myopes	14.22 ± 3.90	2.28 ± 1.48	1.94 ± 0.71	9.92 ± 6.41	3.61 ± 5.79	2.38 ± 13.63
Significance (ANOVA)	$p = 0.11$	$p = 0.002^*$	$p = 0.14$	$p = 0.48$	$p = 0.16$	$p = 0.68$

	Accommodative response				
	Amplitude (D)	Monocular AEI (D)	Binocular AEI (D)	CA/*C* ratio D/D[a]	AC/*C* ratio D/D[b]
Emmetropes	8.88 ± 1.01	0.35 ± 0.23	0.37 ± 0.25	0.067 ± 0.04	3.5 ± 1.0
Myopes	8.12 ± 0.96	0.41 ± 0.27	0.36 ± 0.26	0.061 + 0.03	4.0 ± 1.3
Significance (*t* test)	$p = 0.04^*$	$p = 0.76$	$p = 0.83$	$p = 0.56$	$p = 0.14$
Late-onset myopes	8.20 ± 1.13	0.40 ± 0.29	0.42 ± 0.32	0.063 ± 0.03	3.6 ± 1.4
Early-onset myopes	8.10 ± 0.87	0.41 ± 0.26	0.32 ± 0.22	0.060 ± 0.04	4.2 ± 1.3
Significance (ANOVA)	$p = 0.03^*$	$p = 0.67$	$p = 0.60$	$p = 0.82$	$p = 0.14$

	Tonic accommodation (D)			
	Dark focus	Pinhole	AH	NITM
Emmetropes	0.56 ± 0.51	1.11 ± 0.77	0.13 ± 0.46	0.07 ± 0.73
Myopes	0.49 ± 0.68	0.63 ± 0.77	0.11 ± 0.70	0.14 ± 0.52
Significance (*t* test)	$p = 0.68$	$p = 0.02^*$	$p = 0.92$	$p = 0.72$
Late-onset myopes	0.51 ± 0.61	0.88 ± 0.89	0.10 ± 0.53	0.17 ± 0.44
Early-onset myopes	0.47 ± 0.74	0.43 ± 0.62	0.11 ± 0.84	0.11 ± 0.55
Significance (ANOVA)	$p = 0.91$	$p = 0.03^*$	$p = 0.99$	$p = 0.91$

The *t* test significance refers to non-myopes and myopes. The ANOVA significance refers to late-onset myopes, early-onset myopes, and non-myopes.
[a] Note dimensions are capital D/Greek capital Delta.
[b] Note dimensions are Greek capital Delta/capital D.
* Correlation is significant at the 0.05 level (2-tailed).

−0.38 ± 0.40 D. The distribution of the refractive error after 1 year is shown in Fig. 2A and the change in refractive error is shown in Fig. 2B. We checked to see whether myopia progression was related to the amount of myopia in our sample, but found no significant relationship ($R^2 = 0.02$; $p > 0.3$). We have not, therefore, included the amount of myopia in the next part of the analysis.

A two-stage regression analysis was used to investigate the relationship between accommodative functions and myopia progression: first, a univariate analysis of each factor was carried out (Table 3).

There were nine variables that had correlations ($p \leqslant 0.25$) with myopic progression that warranted inclusion in stage two of the analysis: distance monocular accommodative facility (DMAF); near monocular accommodative facility (NMAF); near binocular accommodative facility (NBAF); positive response time during near monocular accommodative facility (PRTNM); positive response time during near binocular accommodative facility (PRTNB); binocular accommodative error index (BAEI); accommodative hysteresis (AH); monocular lag of accommodation at 33 cm (MLAG); binocular lag of accommodation at 33 cm (BLAG).

The significant multi-colinearity of the various independent variables is shown in Table 2. There are evidently high degrees of correlation between some accommodative functions, and our aim was to ensure that the final regression equation did not contain independent variables which were highly co-correlated. However, at first variables were inserted in a multiple linear regression model with myopia progression as the outcome. The least significant variables were then removed one at a time from the model until only factors with significance of $p \leqslant 0.10$ were included. As a check all the remaining variables were inserted back into this model, one at a time, to ensure that none of the omitted variables became significant in the

Table 2
Correlations between significant independent variables where AOA is the amplitude of accommodation; DMAF is the distance monocular accommodative facility; NMAF is the near monocular accommodative facility; DBAF is the distance binocular accommodative facility; NBAF is the near binocular accommodative facility; DMPRTAF is the positive response time during distance monocular accommodative facility; DBPRTAF is the positive response time during distance binocular accommodative facility; NBPRTAF is the positive response time during near binocular accommodative facility; DMNRTAF is the negative response time during distance monocular accommodative facility; CAC is the convergent accommodation to convergence ratio; MAEI is the monocular the accommodative error index; MLAG is the monocular lag of accommodation at 33 cm; DF is the dark focus accommodation; PH is the pinhole accommodation, and AH is accommodative hysteresis

Correlations	NMAF	DBAF	NBAF	DMPRTAF	NMPRTAF	DBPRTAF	NBPRTAF	DMNRTAF	NMNRTAF	NBNRTAF	BAEI	MLAG	BLAG	PH	AH	NITM
AOA																.30*
DMAF	.51*	.37*	.36*	−.75***	−.27*		−.38***	−.70***	−.27*							
NMAF		.34*	.63*	−.38***	−.57***		−.40***	−.36***	−.61***							
DBAF			.70*	−.42***		−.73***	−.37***			−.47***						
NBAF				−.35**	−.30*	−.51***	−.56***		−.39***	−.58***						
DMPRTAF					.28*	.27*	.33**									
DBPRTAF										.53***						
NBPRTAF								.29*	.46**							
DMNRTAF									.43**						.33*	
CAC														−.28*		
MAEI											.49*	.50*				
MLAG													.64*			−.36*
DF														.45***	−.31*	
PH															−.31*	
AH																.33*

* Correlation is significant at the 0.05 level (2-tailed).
** Correlation is significant at the 0.01 level (2-tailed).
*** Correlation is significant at the 0.005 level (2-tailed).

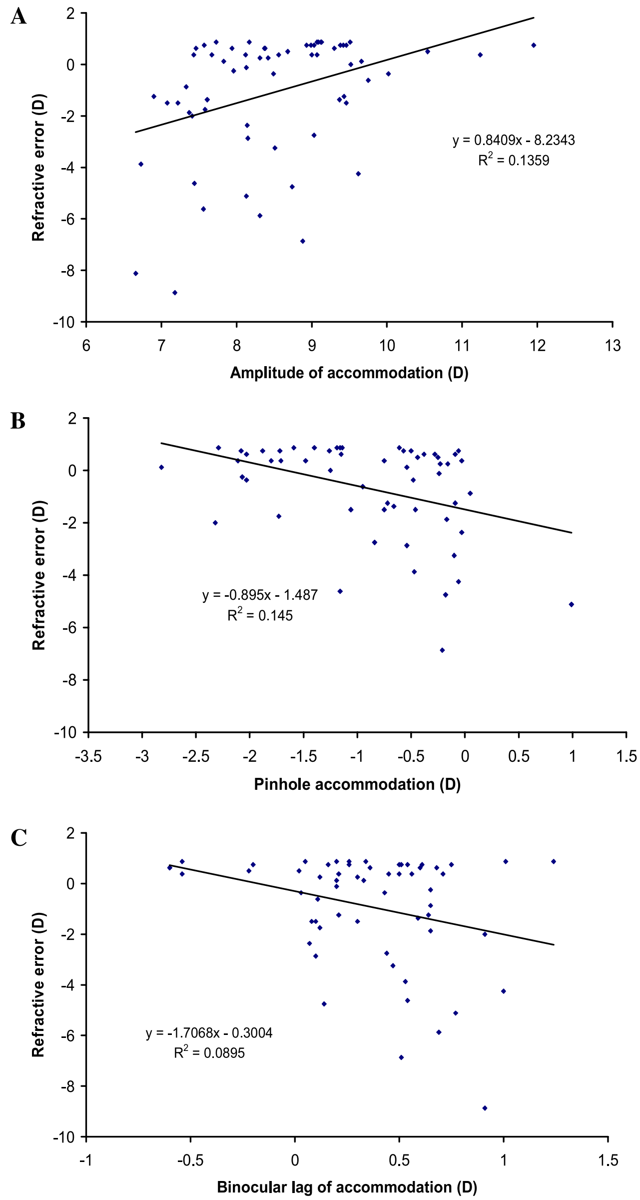

Fig. 1. Scatter plot for: (A) amplitude of accommodation ($p = 0.003$), (B) pinhole accommodation ($p = 0.004$), and (C) binocular lag of accommodation at 33 cm ($p = 0.022$) versus ocular refraction.

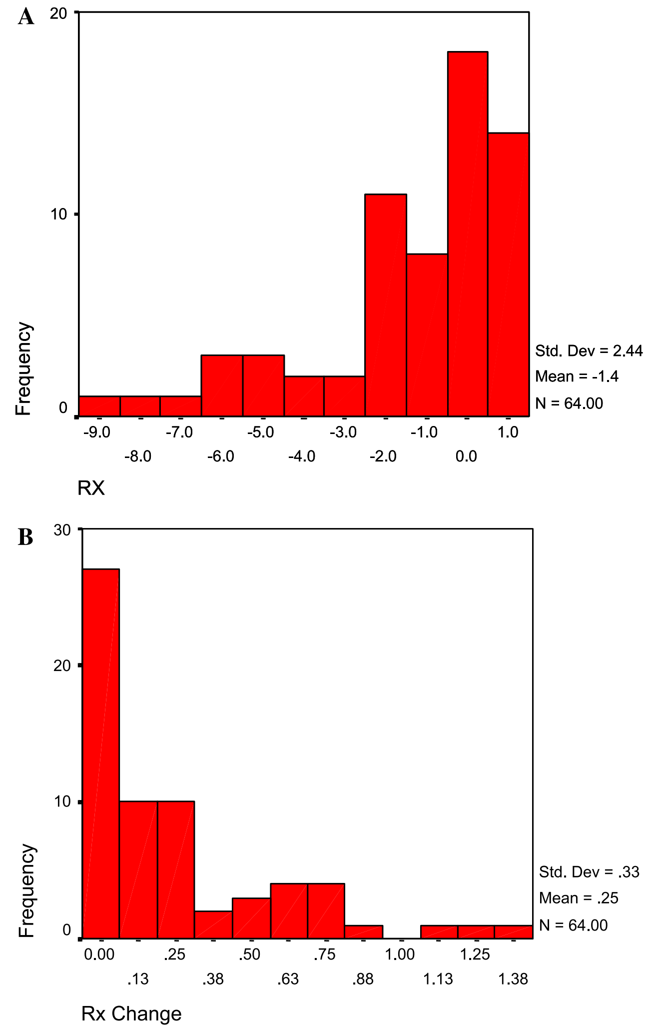

Fig. 2. The distribution of: (A) refractive error after 12 months and (B) change in refractive error after 12 months (positive values indicate progression towards myopia).

presence of the other variables. Finally, a multiple regression model was fitted using two variables (near monocular accommodative facility and binocular accommodative lag at 33 cm) and the fit of the model was evaluated.

A model summary is shown in Table 4 and the model coefficients are shown in Table 5. Binocular lag of accommodation at 33 cm has the highest correlation with myopia progression (Fig. 3). Accommodative facility at near also correlates significantly with myopia progression (Fig. 4).

The very low variance inflation factor (VIF) confirms the co-correlation statistics that the two independent variables are almost completely independent of each other.

The multiple regression equation constructed from the unstandardised coefficient values is:

$$Y = 0.02\alpha - 0.35\beta - 0.45,$$

where Y is the change in refractive error (dioptre per year), α the near (40 cm) monocular accommodative facility (cycles per minute) and β is the binocular lag of accommodation at 33 cm (dioptres).

4. Discussion

4.1. Are accommodative anomalies related to the present refractive error?

The cross-sectional part of this study looked at differences in various accommodative functions of myopes when compared to non-myopes. Non-myopes had, on average, significantly higher amplitudes of accommoda-

Table 3
The table shows the regression coefficients of all the independent variables with myopic progression as the outcome

	Myopia progression	
	Correlations	Significance (p)
Amplitude of accommodation	0.07	0.56
Distance monocular accommodative facility	−0.15	0.23
Near monocular accommodative facility	−0.32	0.01
Distance binocular accommodative facility	0.02	0.91
Near binocular accommodative facility	−0.23	0.07
Positive response time distance monocular accommodative facility	0.12	0.33
Positive response time near monocular accommodative facility	0.20	0.11
Positive response time distance binocular accommodative facility	0.10	0.94
Positive response time near binocular accommodative facility	0.26	0.04
Negative response time distance monocular accommodative facility	−0.02	0.90
Negative response time near monocular accommodative facility	0.11	0.38
Negative response time distance binocular accommodative facility	−0.07	0.61
Negative response time near binocular accommodative facility	−0.04	0.71
CA/C ratio	0.06	0.68
AC/A ratio	0.10	0.44
Monocular accommodative error index	0.84	0.71
Binocular accommodative error index	0.90	0.04
Accommodative hysteresis	0.21	0.16
Monocular accommodation at 6 m	0.51	0.51
Binocular accommodation at 6 m	0.92	0.41
Monocular accommodative lag at 33 cm	0.31	0.02
Binocular accommodative lag at 33 cm	0.35	0.01
Dark focus accommodation	−0.10	0.46
Nearwork-induced transient myopia	0.11	0.43

Table 4
A summary of the multiple regression model with near monocular accommodative facility and binocular lag of accommodation as the regressors

Model summary	Statistic
Sample used	64
Multiple R	0.52
R^2	0.27
Overall p value	<0.001

tion than we found in myopes. There was a significant positive correlation between refractive error and amplitude of accommodation, pinhole accommodation, and binocular lag of accommodation at 33 cm. A second difference between the two groups was that non-myopes had a greater mean distance monocular accommodative facility than myopes. This supports our earlier findings (O'Leary & Allen, 2001).

We also found that late-onset myopes have a greater positive response time during monocular accommodative facility at near when compared to early-onset myopes. No other significant evidence for a relationship between accommodative anomalies and the age of onset of myopia was found. Although there has been a plethora of studies investigating various different functions of accommodation in the two age-of-onset groups, no clear consensus exists.

4.2. Are accommodative functions co-dependent?

Our results indicate that there are correlations within members of groups of accommodative functions such as facility, lag, open-loop and transient effects, and accommodative convergence functions. There is much weaker correlation between members of different groups. We are conscious that this conclusion only applies to the relatively narrow age group of participants examined here, and a much wider age-group, where amplitude of accommodation varies over a much greater range that it did in our participants, will exhibit a different pattern of correlations.

Table 5
The model coefficients including the unstandardised regression coefficients, the standardised regression coefficients, the significance, and the variance inflation factor for near monocular accommodative facility (AFNM) and binocular lag of accommodation at 33cm (BLAG)

Variables	Unstandardised coefficients		Standardised coefficients	Significance	Collinearity statistics (VIF)
	Beta	Standard error			
(Constant)	0.45	0.10			
AFNM	−0.02	0.01	−0.368	0.001	1.02
BLAG	0.35	0.10	0.398	0.001	1.02

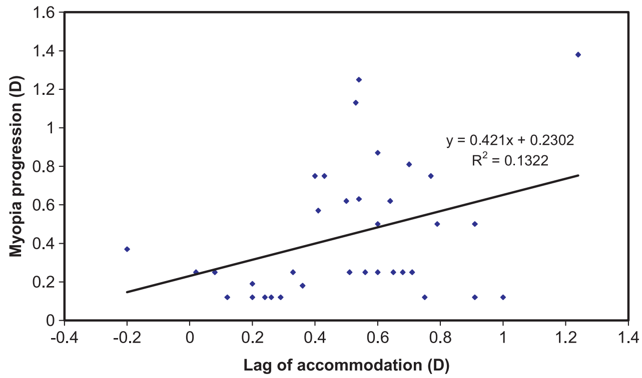

Fig. 3. Scatter plot for myopia progression versus binocular lag of accommodation for a 33 cm stimulus.

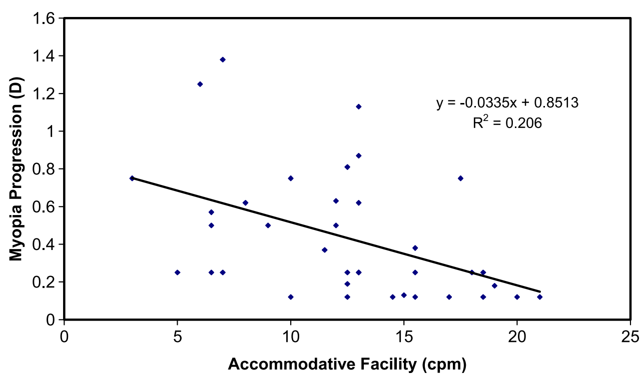

Fig. 4. Scatter plot for myopia progression versus near monocular accommodative facility.

We confirm earlier reports that open-loop accommodation measures (pinhole accommodation and dark focus of accommodation) are well correlated (Leibowitz & Owens, 1975a, 1975b), as are accommodative after-effects (nearwork-induced transient myopia and accommodative hysteresis (Ong & Ciuffreda, 1995)). Accommodative response times to negative lenses were all highly correlated (monocular and binocular positive response times for distance and near), but accommodative response times to positive lenses (monocular and binocular negative response times for distance and near) appeared to be uncorrelated with each other. This suggests that there is an underlying factor that affects PRT, but not NRT, in our sample. We suspect that this factor is the asymmetry in the effect of positive and negative blur on visual thresholds. Radhakrishnan, Pardhan, Calver, and O'Leary (2004a) and Radhakrishnan, Pardhan, Calver, and O'Leary (2004b) showed that in myopes negative lens blur has a much smaller effect on low and mid-frequency contrast sensitivity in myopes when compared with non-myopes. Positive lens-induced blur produced roughly equal declines in contrast sensitivity in myopes and non-myopes.

We were interested to note a very significant correlation between nearwork-induced transient myopia and accommodative lag at 33 cm. We believe that this has not been reported previously. Both measures can be viewed as a deficiency in the rate at which blur-driven changes in accommodation occur for either near viewing (lag) or post-near viewing (transient myopia). Wolffsohn et al. (2003) reported that myopes show an increased lag of accommodation for near targets and increased nearwork-induced transient myopia when compared with emmetropes, however, no correlations between these functions were reported.

4.3. Are accommodative anomalies related to progressing myopia?

4.3.1. Lag of accommodation

The results from the multiple regression analysis indicate that the binocular lag of accommodation at near (33 cm) and near monocular accommodation facility are the two best independent accommodative functions as predictors of myopia progression. Many of the accommodative facility measurements were highly correlated and any one of a number of them might have been included in the final model without a great loss of power. The monocular and binocular lags of accommodation were also highly correlated ($r = 0.637$, $p = 0.0005$). Therefore it is appropriate to say that accommodative lag and accommodative facility are generally related to myopia progression.

The present study is in accordance with previous work (Abbott et al., 1998; Gwiazda et al., 1995a; O'Leary & Allen, 2001; Vera-Diaz et al., 2002) demonstrating an increased lag of accommodation in participants with progressing myopia. This result suggests that participants with progressing myopia may have extended periods of retinal defocus during nearwork.

4.3.2. Facility of accommodation

Accommodative facility was a significant factor for myopia progression in young adults although no difference in performance in near accommodative facility was found between non-myopes and myopes in the cross-sectional study, possibly because participants in both the myopic and emmetropic groups exhibited a myopic increase in their refractive error over the 12 months.

The distance positive response time (time to accommodate through a −2.00 DS lens) was longer in the participants who became more myopic. This is in agreement with previous studies in which progressing myopes exhibited a reduced performance at static and dynamic tests (Abbott et al., 1998; Seidel, Gray, & Heron, 2003). Although the results from accommodative facility cannot be applied directly to the dynamic accommodation response in natural viewing the results suggest that delays in attaining focus when changing fixation from far to near could lead to brief periods of hyperopic defocus. If this retinal defocus accumulates in additional to the within-task defocus discussed above then substantial periods of defocus could occur. This accumulated defocus would be maximal in people who spent substantial periods of the day switching between reading and more distant visual; tasks—for example, students.

Amplitude of accommodation and open-loop accommodation are not factors in myopia progression, although we find a clear relationship between myopia and both amplitude and pinhole accommodation. We believe this favours the explanation given by Mutti et al. (2000) that the enlargement of the eye in developing myopes causes these changes in accommodation functions.

4.3.3. The importance of the lag of accommodation

The only accommodative function that correlated with both the amount of myopia and the progression of myopia was the binocular lag of accommodation at 33 cm. This interesting finding indicates that lag may be particularly important in increasing the risk of progression in myopes as their myopia increases. We note that Gwiazda et al. (1995a) found a very high correlation ($R^2 = 0.77$) between lag of accommodation and myopia progression in their young subjects. Although we confirm that accommodative lag is a significant predictor of myopia progression, the correlation in our study is much lower ($R^2 = 0.13$). This may demonstrate a shift in the importance of lag as a factor in myopia progression as people get older, and may protect those approaching presbyopia from becoming short-sighted.

Studies attempting to relate the gradients of the accommodative stimulus–response function to myopia progression have been equivocal. There have been considerable methodological differences in these studies with different results being found when negative lenses and altered target distance have been used to stimulate accommodation (Abbott et al., 1998; Gwiazda et al., 1995a; Rosenfield et al., 2002). However, at the higher stimulus levels myopes have generally demonstrated a greater lag of accommodation than emmetropes (Abbott et al., 1998; Bullimore, Gilmartin, & Royston, 1992; Chat & Edwards, 2002; Gwiazda et al., 1993; McBrien & Millodot, 1986b). The present study confirms this finding. Accommodative responses (both monocular and binocular) to a real target at 6 m were not significantly related to myopia progression.

4.3.4. Oculomotor factors

The vergence system has been suggested as a possible link between nearwork and myopia (Goss & Zhai, 1994; Norton & Gamlin, 1999). Previously myopes have been found to have either a higher AC/*A* ratio when compared to emmetropes (Gwiazda et al., 1999; Jiang, 1995; Mutti et al., 2000), or a similar AC/*A* ratio as emmetropes (Chen et al., 2003). CA/*C* ratios do not vary with refractive error group (Jiang, 1995; Rosenfield & Gilmartin, 1988a, 1988b). The cross-links between accommodation and vergence may be innervated by both the fast and slow blur-driven responses (Rosenfield & Gilmartin, 1988a, 1988b). If an imbalance in the autonomic input to the ciliary muscle, particularly a deficit in the sympathetic input, is a contributing factor to myopia progression (Gilmartin & Winfield, 1995) then one would expect the AC/*A* ratio to be elevated due to the additional demand placed upon the fast blur-driven accommodative response. The findings of this study would suggest that the balance of the autonomic input to the ciliary muscle does not play a significant role in myopia progression in young adults as neither the AC/*A* ratio nor the CA/*C* ratio contributed significantly to myopia progression. However, Mutti et al. (2000) suggested that an elevated AC/*A* ratio (greater than 5.84 Δ/D) was a significant risk factor for the onset of myopia. Interestingly, although there were no significant differences between the groups in the present study, of the five participants with AC/*A* ratios greater than 5.60 Δ/D four of those participants exhibited a myopic shift of greater than −0.50 D over the 12 month period. Further investigation, with a larger sample, is still necessary to clarify this relationship.

4.3.5. Open-loop and transient effects

Neither tonic accommodation nor near-induced transient myopia was a significant risk factor for myopia progression in the present study. This appears to conflict with an earlier study (Vera-Diaz et al., 2002), and it is possible that methodological differences can explain the apparent conflict. The time delay between inducing a response and measuring the response in our experiments appears to be longer than in the earlier work (Vera-Diaz et al., 2002). However, we note a strong correlation between the transient functions measured in our experiments, and this indicates that our measurements are valid indications of differences between participants, albeit slightly different from the characteristics measured in the earlier work.

5. Conclusions

In summary, the two key accommodative functions that distinguish between participants with a stable refractive error and participants who exhibited an increase in refractive error towards myopia are accommodative facility and the lag of accommodation. Both these factors affect the retinal defocus and suggest that retinal defocus is a significant factor in myopia progression in young adults. Because lag is also related to the amount of myopia, it may be a particularly important risk factor in the progression of higher amounts of myopia.

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