Changes in dynamics of accommodation after accommodative facility training in myopes and emmetropes

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Abstract

This study evaluates the effect of accommodative facility training in myopes and emmetropes. Monocular accommodative facility was measured in 9 myopes and 9 emmetropes for distance and near. Subjective facility was recorded with automated flippers and objective measurements were simultaneously taken with a PowerRefractor. Accommodative facility training (a sequence of 5 min monocular right eye, 5 min monocular left eye, 5 min binocular) was given on 3 consecutive days and facility was re-assessed on the fifth day. The results showed that training improved the facility rate in both groups. The improvement in facility rates were linked to the time constants and peak velocity of accommodation. Some changes in amplitude seen in emmetropes indicate an improvement in facility rate at the expense of an accurate accommodation response.

Accommodative facility is a clinical test that enables an eye-care practitioner to evaluate the ability of the eye to alter accommodation rapidly and accurately. The dioptric stimulus to accommodation is alternated between two different levels, with the number of cycles between the two levels in a given time period being recorded. The stimulus level is changed immediately after the patient reports clarity of vision following each previous lens change (Hennessey, Iosue & Rouse, 1984; Zellers, Alpert & Rouse, 1984; Rosenfield, 2009). The clinical standard for accommodative facility testing was described by Zellers et al. (1984).

Accommodative facility results have been shown to be a useful predictor of potential visual discomfort (Kiely, Crewther & Crewther, 2001) and also of academic success (Kedzia, Tondel, Pieczyrak & Maples, 1999). Low accommodative facility is also used as a diagnostic sign for accommodative insufficiency. Differences in performance have been found between symptomatic and asymptomatic patients (Hennessey et al., 1984) and different refractive error groups (Allen & O'Leary, 2006; Jiang, 1995; O'Leary & Allen, 2001; Pandian, Sankaridurg, Naduvilath, O'Leary, Sweeney, Rose & Mitchell, 2006). Both young adult myopes (Allen & O'Leary, 2006; Jiang, 1995; O'Leary & Allen, 2001) and 6-7 year old myopes (Pandian et al., 2006) have been shown to exhibit significantly lower distance facility rates when compared to emmetropes, although this difference between the refractive groups was not present at near. Allen and O'Leary (2006) showed that facility of accommodation and accommodative lag were the two main independent accommodative predictors of myopia progression in another cohort of young adults, with lower facility rates being associated with increased myopia progression.

In order to clarify the source of the differences in accommodative facility between myopes and emmetropes, Radhakrishnan, Allen & Charman (2007) collected simultaneous, objective measurements of the dynamic changes in accommodation response while carrying out distance and near accommodative facility tests. Like earlier authors, they found that both objective and subjective measurements of accommodative facility showed a significantly lower distance facility rate in myopes when compared to emmetropes. Myopes exhibited lower velocities of accommodation and disaccommodation during distance facility measurement, along with longer time intervals. At near, the accommodative facility rate was similar in both refractive groups: no significant differences in velocity of accommodation were found between the two groups, although velocity of disaccommodation was relatively lower in myopes when compared to emmetropes.

Various clinical studies have suggested that remediation of accommodation dysfunction by vision training, including accommodative facility training, is successful in alleviating patient symptoms and improving accommodation performance (Daum, 1983; Hoffman & Cohen, 1973; Levine, Ciuffreda, Selenow & Flax, 1985; Wold, Pierce & Keddington, 1978). However, detailed objective assessment of the improved functions in an experimental setting is required to fully understand the nature of any improvements. Previous attempts at assessing any changes in the dynamics of accommodation with accommodative facility training (Bobier & Sivak, 1982; Liu, Lee & Jang, 1979) have used only a few subjects, with the subjects being symptomatic to near problems or having initially low accommodative facility rates. Bobier & Sivak (1982) showed that, after 3 to 6 weeks of accommodative facility training, significant reductions in latency occurred for 4 of their 5 subjects, although the majority of improvement was seen after 1 week Four subjects also showed a reduction in positive response time and 3 subjects showed a reduction in negative response time. Liu et al. (1979) found that all 3 of their subjects showed an improvement in the speed of negative accommodation response and 2 also demonstrated an improvement in positive accommodation response after a combination of convergence and facility training, although latencies were not generally improved with training. This previous work occurred before the recent upsurge of interest in the potential role of accommodative function in myopia progression, and therefore did not investigate myopes and emmetropes separately.

It is possible that the reduced distance accommodative facility demonstrated by myopes precedes the development of myopia (Allen & O'Leary, 2006) and contributes in some way to its progress, perhaps by inducing periods of retinal blur. If, then, training improves accommodative facility, it may help to control the subsequent progression of the refractive error. It would therefore be beneficial to better understand the details of the effectiveness of training in improving accommodative facility. Any study should provide detailed objective data regarding the accommodative responses (which in clinical practice are normally assumed to be accurate due to the reporting of a clear image during the subjective measurement) made by both refractive groups and how these are affected by the training.

The present experiments were conducted to make objective, simultaneous measurements of the dynamic changes in accommodation response during distance and near facility testing in non-symptomatic emmetropes and myopes, before and after 3 daily sessions of training.

Methods:

Subjects

Eighteen visually normal observers participated in the main study. The nine emmetropic subjects had a mean spherical equivalent refractive error of +0.28 ± 0.15 D (range Plano to +0.50D) with a mean age of 22 ± 2.0 years (range 20 to 25 years). The mean spherical equivalent refractive error in the nine myopes was -4.00 ± 2.71 D (range -1.50D to -9.50D) and their mean age was 21 ± 1.4 years (range 20 to 23 years). All the myopic subjects were corrected with soft contact lenses. All subjects had a visual acuity of at least 6/5 and were screened to exclude astigmatism greater than 1.00D, myopic retinal degeneration, amblyopia or any ocular disease. The subject numbers were chosen following a power analysis based on a previous study on objective accommodative facility (Radhakrishnan et al., 2007). Subjects gave informed consent for taking part in the study, which followed the tenets of the Declaration of Helsinki and was approved by the Anglia Ruskin University Ethical Committee.

An additional, different, matched group of 18 visually-normal observers participated in a control study designed to ensure that any post-training changes in facility characteristics were associated with the training, rather than simply being due to repeated testing. The nine emmetropic subjects had a mean spherical equivalent refractive error of +0.20 ± 0.17 D with a mean age of 22.9 ± 2.7 years. The mean spherical equivalent refractive error in the nine myopes was -3.50 ± 2.15 D and their mean age was 23 ± 3.3 years. The myopic subjects were corrected with soft contact lenses. Like the subjects in the main study, the control subjects had a visual acuity of at least 6/5 and were screened to exclude astigmatism greater than 1.00D, myopic retinal degeneration, amblyopia or any ocular disease.

Subjective accommodative facility measurements

Monocular accommodative facility for the right eye was investigated at both 6m and 0.4m. Accommodative facility in the distance was measured using a Plano/–2.00D lens combination mounted in a flipper with the subject viewing 6/9 letters placed 6m away (i.e. the vergence of the accommodative stimulus at the cornea changed between -0.17 and -2.10 D, assuming a lens vertex distance of 15mm) while, at near (0.4 m), reduced 6/9 letters were viewed through a flipper consisting of +2.00D/-2.00D lens combination (accommodative stimulus vergence change between -0.50 and -4.22 D): the 6/9 letter size used is typical of that employed in clinical practice (Rosenfield, 2009). In both cases the left eye was occluded with an 87C Wratten filter. This filter transmits infrared light, allowing objective dynamic readings of accommodation to be obtained with an infra-red autorefractor (PowerRefractor, Multichannel Systems, Rütlingen, Germany), while occluding the visual input to that eye.

The subjects 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 tap the table. I will then change the lens and the letters might be blurred again; tap the table 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 lenses in a 1-minute period*."

The subjective accommodative facility was measured with semi-automated flippers (Vision CRC, Sydney) (Pandian et al., 2006; Radhakrishnan et al., 2007). Each test lasted 60 seconds, the time at which each lens flip occurred being recorded. The subjects were given training with the test for 20 seconds prior to taking the measurements. All the subjective accommodative facility measurements were performed by a clinician who was masked to the subject's refractive error group.

Objective accommodative facility measurements

The objective measurements were obtained using a PowerRefractor (Multichannel Systems, Germany) which dynamically recorded the refractive error during the facility measurements The data obtained from a PowerRefractor have been shown to be both valid and repeatable (Allen, Radhakrishnan & O'Leary, 2003; Choi, Weiss, Schaeffel, Seidemann, Howland, Wilhelm & Wilhelm, 2000; Hunt, Wolffsohn & Gilmartin, 2003). The PowerRefractor measurements were started in synchrony with the subjective facility measurement. The start button on the flippers produced a 'beep' which was used for initialising the objective measurements in synchrony with the subjective data collection. Since the synchronisation of the two measurements was not automated, there could have been some variability between the start of the two measurements. However, the variability is likely to be relatively small, as in Radhakrishnan et al. (2007), and to be similar before and after facility training. The measurements were obtained from the left eye, the PowerRefractor being placed at 1m directly in front of the left eye, while the stimulus was presented to the right eye. The left-eye measurements reflect the accommodative changes in the right eye, as it has been shown that accommodation is synchronized in the two eyes (Campbell, 1960). The flippers were presented in front of the right eye only. The PowerRefractor was set on ‘monocular’ mode, which measures refraction only in the vertical meridian. Control measurements suggested that the small convergence movements elicited in the left eye by accommodation in the right eye had only minor effects on the PowerRefractor measurements (see also Wolffsohn, Hunt & Gilmartin, 2002). The measurements were obtained at a rate of 25Hz. Due to large variations in calibrations among subjects (Allen et al., 2003; Choi, Weiss, Schaeffel, Seidemann, Howland, Wilhelm & Wilhelm, 2000; Gekeler, Schaeffel, Howland & Wattam-Bell, 1997; Seidemann & Schaeffel, 2003; Schaeffel, Weiss & Seidel, 1999) the PowerRefractor was calibrated for each subject individually in order to achieve optimal measurement validity during the study.

For calibration the left eye was occluded with the 87C Wratten filter while the right eye fixated a 6/9 letter placed at 6 m. During steady fixation with the right eye, trial lenses (+4.00 DS to –1.00 DS at 1 D intervals) were placed in front of the Wratten filter and left eye. Measured left-eye refraction was compared to the refraction expected from the trial lenses. The correction factor was taken from the slope and intercept of the linear regression and incorporated into the PowerRefractor measurements from that subject. Note that this procedure assumes that, with a plano lens, there is zero accommodative response to the 6m target: in practice conventional refractive procedures leave the eye slightly myopic for a 6m target (e.g. Rabbetts, 1998), so that the absolute levels of recorded response may be slightly offset, although the changes are correct.

With the main group of subjects, subjective and objective accommodative facility data were obtained at a baseline visit (day 1) and again on the day following the 3 daily accommodative facility training sessions, i.e. on day 5, 4 days after the initial measurements (see below). Calibration and data collection took approximately 15 min for each subject on each occasion. Distance facility was always measured first followed by near facility.

With the control subjects only subjective facility data were recorded. Measurements were taken on day 1 and were repeated on day 5, with no training being given between day 1 and day 5.

Accommodative facility training

The accommodative facility training for the main group of subjects occurred on the 3 days following the baseline pre-training assessment of accommodative facility. All training occurred under supervision in our laboratory. The procedure was essentially the same as during the subjective near facility measurements, except that rates were not recorded. The subjects were instructed to hold a set of +2.00D/-2.00D lens flippers in front of their eyes while viewing reduced 6/9 text at 0.4m. The subjects were instructed as follows "*You should look at the text and try to keep it clear while looking through the flipper lenses. When you first put the flipper lenses in front of your eye(s) the text should blur and then become clear again. As soon as it is clear please flip the lenses. Upon flipping the lenses the letters might blur again, as soon as you can see the text clearly again re-flip the lenses. Continue this process until you hear the stop-watch make an audible 'beep' after 5 minutes*." The training consisted of 5 minutes monocular facility training of the right eye (the left eye was patched), followed by 5 minutes monocular facility training of the left eye (the right was patched), followed by 5 minutes of binocular facility training. This training regime occurred at the same time of day for each subject on 3 consecutive days (days 2-4).

Data analysis

A sample of the objective dynamic measurement data obtained from the PowerRefractor is shown in Figure 1. Note the asymmetries between accommodation and disaccommodation in some cycles and the usual fluctuations in accommodation response. In general there is a marked time lag between each stimulus change and the corresponding response.

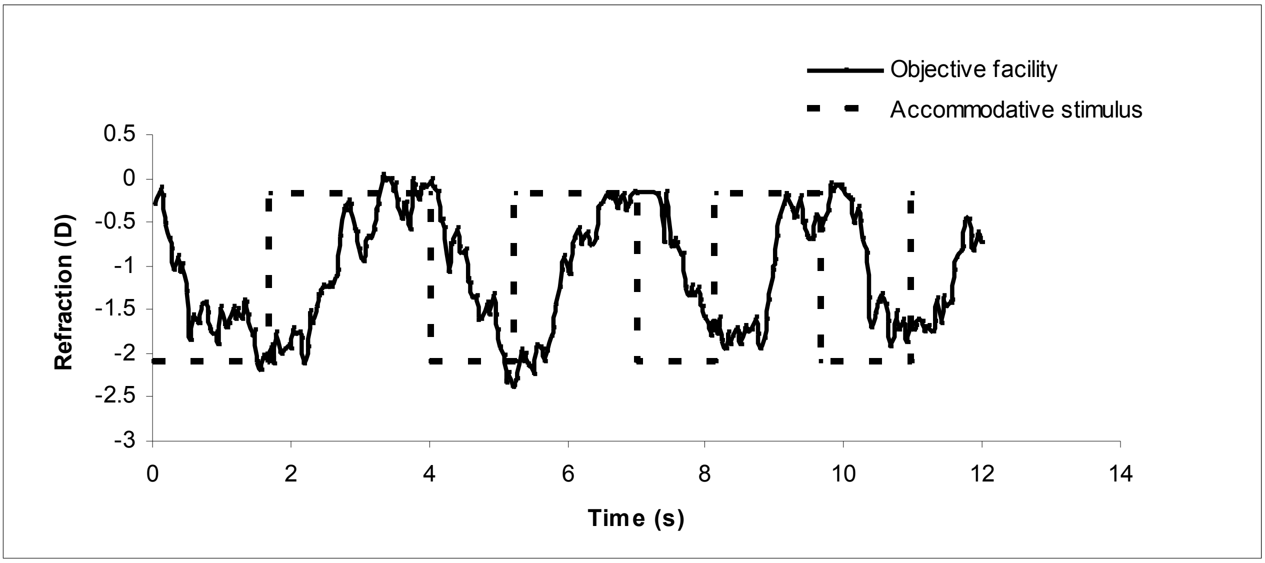


Figure 1: *Example of part of the objective record of accommodation during a distance facility test. The Plano/-2D flipper changed the target vergence between -0.17 D and -2.10 D. The dashed line shows the times at which stimulus changes occurred and the continuous record the corresponding level of accommodation. An increase in negative refraction corresponds to a positive accommodation response*

(positive accommodation) and a decrease to a negative response (disaccommodation).

The records were analyzed using the same techniques as those employed by Radhakrishnan et al. (2007) i.e. the peak-fitting module in Origin Pro 7 (Micoral Software Inc., USA). The peak-fitting module was used to automatically detect the peak locations, using an irregular sinusoid function. No averaging was done and each response was analyzed individually. The time constants for accommodation and disaccommodation were calculated by assuming that the accommodation response during the changes could be described by the exponential equations:

$\mathrm{A} = A_H - \mathrm{a} \times \mathrm{e}^{-t/\tau}$ for accommodation and

$\mathrm{A} = A_L + \mathrm{a} \times \mathrm{e}^{-t/\tau}$ for disaccommodation

where, A is the accommodative response, A_H and A_L are the accommodative responses at the "near" and "distance" peaks respectively, t is time in seconds after commencement of the response and τ is the time constant in seconds. The peak-to-peak amplitude of accommodative response (a = A_H - A_L) for each accommodative half-cycle was calculated from the data obtained from the peak locations. The amplitude data were then used to calculate the response levels when 10% and 90% of the accommodative response amplitude was reached and the PowerRefractor records were analysed to find the corresponding times, $\mathbf{t}_{10}$ and $\mathbf{t}_{90}$. These values were then used to calculate the time constants using a derivation from the above equation where,

$$\tau = \frac{t_{90} - t_{10}}{\ln 9}.$$

On the above assumption of an exponential response change, the maximum velocities, V, of accommodation and disaccommodation were calculated using the equation $V = (dA/dt)_{t=0} = a/\tau$.

One myopic subject had a subjective facility rate of only 2 to 3 cycles/minute for distance and near facility measurements. Further, due to some missing data in the objective measurements caused by blinks, objective facility measurements could not be computed accurately for this subject. Therefore, this myopic subject was excluded from data analysis and the results section presents data from 8 myopes and 9 emmetropes.

Results

Subjective accommodative facility

Facility rates

Monocular subjective accommodative facility rate for emmetropes and myopes before and after facility training are shown in Table 1. A significant improvement in facility rate was found in both groups following the facility training (repeated measures ANOVA: $F_{1,16} = 22.9$; $p = 0.0005$). Refractive group of the subjects had no significant effect on this difference ($F_{1, 16} = 0.31$; $p = 0.586$).

		Subjective facility (cycles/minute)	Objective facility Calculated with peak fitting module (cycles/minute)
Pre -Training			
Emmetropes	Distance	18.2 ± 1.9	19.3 ± 2.5
	Near	14.1 ± 3.8	13.8 ± 3.5
Myopes	Distance	14.5 ± 5.5	15.2 ± 5.9

	Near	13.8 ± 5.6	14.5 ± 6.1
Post - Training			
Emmetropes	Distance	21.8 ± 3.3	23.0 ± 3.7
	Near	20.2 ± 4.4	19.3 ± 5.6
Myopes	Distance	19.1 ± 5.2	20.8 ± 4.9
	Near	17.9 ± 5.6	18.3 ± 7.4

Table 1: *Subjective and objective facility rates before and after training. Data are shown for the two refractive groups, tested at both distance and near***.**

Corresponding data for the control group, to which no training was given, are shown in Table 2. Monocular subjective accommodative facility rate for emmetropes and myopes showed no significant improvement between the first (Day 1) and the second (Day 5) measurements at distance (repeated measures ANOVA: $F_{1,16} = 0.86$; $p = 0.37$) and near ($F_{1,16} = 0.05$; $p = 0.82$) . Refractive group of the subjects had no significant effect on this difference ($p>0.05$).

		Facility rate (cycles/min)	
		Day 1	Day 5
Emmetropes	Distance	18.0 ± 1.8	18.7 ± 5.1
	Near	14.6 ± 3.0	14.9 ± 3.0
Myopes	Distance	10.1 ± 4.5	11.2 ± 4.6
	Near	10.9 ± 3.8	10.9 ± 4.8

Table 2: *Mean subjective facility rates on Day 1 and Day 5 and their standard deviations, for the untrained control group*

Positive and negative response times

The mean positive and negative subjective response times (i.e. the intervals between more- and less-negative, and less- and more-negative lens flips) for myopes and emmetropes are shown in Table 3. The positive response time corresponds to accommodation, the negative to disaccommodation. Note that the standard deviations are much greater for the myopic group, which showed much greater inter-subject variability. Analysis of variance was performed with response times as the dependent variable and refractive error as the independent variable. Both before and after facility training, repeated measures Analysis of variance showed no significant difference between the two refractive groups for distance and near facility for positive and negative response times ($p>0.05$:Table 3). The negative response time (disaccommodation) was found to be lower than the positive response time (accommodation) for near facility measurements before training (repeated measures ANOVA: $F_{1,17}=9.40$; $p=0.007$). However, after facility training, this difference between positive and negative response times did not exist (repeated measures ANOVA: $F_{1,17}=0.48$; $p=0.499$).

			Emmetropes (Mean ± SD) seconds	Myopes (Mean ± SD) seconds
Pre – Training				
Positive response time	Distance	Subjective	1.69 ± 0.32	2.52 ± 1.34
		Objective	1.68 ± 0.29	2.57 ± 1.51
	Near	Subjective	2.63 ± 1.18	2.98 ± 1.59
		Objective	2.64 ± 1.04	3.04 ± 1.51
Negative response time	Distance	Subjective	1.62 ± 0.68	2.17 ± 1.24
		Objective	1.67 ± 0.60	2.55 ± 0.74
	Near	Subjective	1.74 ± 0.43	2.00 ± 1.08
		Objective	1.89 ± 0.36	1.99 ± 1.01
Post – Training				
Positive response time	Distance	Subjective	1.42 ± 0.49	1.66 ± 0.43
		Objective	1.43 ± 0.35	1.65 ± 0.35
	Near	Subjective	1.82 ± 0.79	1.85 ± 0.59
		Objective	1.72 ± 0.58	1.89 ± 0.70
Negative response time	Distance	Subjective	1.13 ± 0.12	1.28 ± 0.37
		Objective	1.25 ± 0.26	1.40 ± 0.33
	Near	Subjective	1.14 ± 0.14	1.40 ± 0.39
		Objective	1.34 ± 0.35	1.48 ± 0.96

Table 3*: Subjective and objective response times at distance and near, before and after training in the emmetropic and myopic groups.*

In the untrained control group there were no significant differences between the first (Day 1) and second (Day 5) measurements of mean positive and negative subjective response times at either distance and near ($p>0.05$).

			Response time (secs)	
			Day 1	Day 5
Emmetropes	PRT	Distance	1.32 ± 0.20	1.22± 0.33
		Near	2.04 ± 0.31	2.05 ± 0.28
	NRT	Distance	1.99 ± 0.22	2.15 ± 0.98
		Near	2.21 ± 0.88	2.11 ± 1.18
Myopes	PRT	Distance	1.62 ± 0.46	1.34 ± 0.25
		Near	3.27 ± 1.64	3.22 ± 1.83
	NRT	Distance	5.81± 4.69	4.88 ± 3.20
		Near	2.90 ± 1.70	2.93 ± 1.58

Table 4: *Mean measurements and standard deviations for subjective positive (PRT) and negative (NRT) response times (seconds) in the control group*

Objective accommodative facility

Facility rates

The objective facility rate was calculated by averaging the number of positive and negative peaks in a run (60 seconds data). Objectively-measured accommodative facility rates are shown in Table 1. They differ slightly from the subjective rates because of the variable intervals between the times at which the lenses were changed and the subsequent response extrema, as illustrated in Fig.1.

The mean objective positive and negative response times (i.e. the time intervals between successive accommodation maxima and minima as established using the peak-fitting procedure) for myopes and emmetropes are shown in Table 3. Analysis of variance showed similar results to those found for subjective response times ($p>0.05$).

Amplitude

The amplitude data calculated using the peak-fitting technique (i.e. the differences between the highest and lowest levels of response) before and after accommodative facility training in the two refractive groups are shown in Table 5. None of the changes in amplitude after facility training reaches statistical significance ($p>0.2$ in all cases by t-test). Statistical analysis showed a significant interaction between distance, refractive error group and facility training (ANOVA: $F_{1,2131}=26$; $p=0.0005$).

Pre-training and post-training, myopes show larger amplitudes than emmetropes for both accommodation and disaccommodation cycles at distance and near (pre-training: $F_{1,934}=102$; $p=0.0005$; post training: $F_{1,1196}=417$; $p=0.0005$). A significant interaction was found between refractive group and distance at which the measurements were made (ANOVA: $F_{1,1196}=37$; $p=0.0005$).

The magnitudes of the accommodation changes in both refractive groups were substantially smaller than the corresponding stimulus changes at both distance (stimulus change 1.93 D) and near (stimulus change 3.72 D), implying substantial errors in accommodation. Indeed, if reading 6/9 demands that the error of focus be

0.5 D or less (e.g. Rabbetts, 1998) it is difficult to believe that subjects could always discriminate the 6/9 letter detail before they initiated the lens changes.

		Objective amplitude (D) of accommodation	Objective amplitude (D) of disaccommodation
Pre –Training			
Emmetropes	Distance	0.90 ± 0.72	0.91 ± 0.72
	Near	1.70 ± 1.54	1.71 ± 1.45
Myopes	Distance	1.66 ± 0.73	1.67 ± 0.71
	Near	2.31 ± 1.03	2.28 ± 1.04
Post – Training			
Emmetropes	Distance	0.79 ± 0.84	0.79 ± 0.81
	Near	1.19 ± 1.23	1.21 ± 1.21
Myopes	Distance	1.74 ± 1.07	1.70 ± 1.03
	Near	2.92 ± 1.38	2.93 ± 1.35

Table 5: *Amplitudes (D) of accommodation and disaccommodation for different conditions and refractive groups. The stimulus changes induced by the flipper lenses at distance and near are 1.93 and 3.72 D respectively. Note that peak-to-peak response amplitudes are much smaller for emmetropes*

Time constants

The time constants for the accommodation and disaccommodation cycles for distance and near, before and after facility training are given in Table 6. Facility training had a significant effect on time constants (ANOVA: $F_{1,2131}$=103; p=0.0005).

The time constants were found to be higher in myopes than in emmetropes. As might be expected from the relative magnitudes of the stimulus changes involved, Table 6 also shows that near time constants were larger in magnitude than the distance time constants in both the refractive groups. Following accommodative facility training, the time constants in both refractive groups appear to have reduced in magnitude. Analysis of variance showed a significant difference in the time-constant values between myopes and emmetropes both before ($F_{1,934}$=19.3; p=0.0005) and after facility training ($F_{1,1196}$=162; p=0.0005). There was also a significant difference between time constants for distance and near facility measurements (before training: $F_{1,934}$=9.7; p=0.002; after training: $F_{1,1196}$=10.2; p=0.001).

		Time constant of accommodation	Time constant of disaccommodation
Pre -Training			
Emmetropes	Distance	0.24 ± 0.22	0.26 ± 0.29
	Near	0.39 ± 0.58	0.39 ± 0.42
Myopes	Distance	0.46 ± 0.50	0.39 ± 0.35
	Near	0.46 ± 0.36	0.44 ± 0.42
Post – Training			
Emmetropes	Distance	0.15 ± 0.21	0.14 ± 0.19
	Near	0.22 ± 0.24	0.16 ± 0.19
Myopes	Distance	0.31 ± 0.22	0.30 ± 0.19
	Near	0.35 ± 0.24	0.33 ± 0.22

Table 6: *Time constants of accommodation and disaccommodation for different conditions and refractive groups.*

Maximum velocity of accommodation and disaccommodation

Table 7 shows the mean maximum velocity of accommodation and disaccommodation in myopes and emmetropes for accommodative facility measurements at distance and near, before and after facility training. Facility training had a significant effect on maximum velocities of accommodation (ANOVA: $F_{1,1077}$= 20.2; p=0.0005) and disaccommodation (ANOVA: $F_{1,1053}$=25; p=0.0005), which all increased, and a statistically significant interaction was found between distance, refractive error group and facility training for maximum velocity of accommodation and disaccommodation ($p<0.01$).

Pre-training, emmetropes show a higher velocity of accommodation when compared to myopes, especially at near. Analysis of variance showed a significant difference in the velocity of accommodation between myopes and emmetropes ($F_{1,473}= 6.4$; $p=0.012$) but not for velocity of disaccommodation ($F_{1,460}= 0.325$; $p=0.57$). No significant difference was found in velocity of accommodation (ANOVA: $F_{1,603}= 0.15$; $p=0.696$) and disaccommodation (ANOVA: $F_{1,592}= 0.02$; $p=0.888$) between the two refractive groups in the post-training session.

		Velocity (D/s) of accommodation	Velocity (D/s) of disaccommodation
Pre -Training			
Emmetropes	Distance	6.49 ± 6.84	7.40 ± 7.78
	Near	10.13 ± 9.05	8.71 ± 9.26
Myopes	Distance	6.07± 5.32	6.42 ± 5.46
	Near	7.30 ± 6.24	8.88 ± 7.21
Post – Training			
Emmetropes	Distance	9.80 ± 8.14	10.28 ± 8.01
	Near	8.90 ± 7.68	10.47 ± 8.54
Myopes	Distance	7.85 ± 5.58	8.13 ± 7.68
	Near	11.31 ± 7.11	12.43 ± 8.41

Table 7: *Mean values of the maximum velocity of accommodation ($V = (dA/dt)_{t=0} = a/\tau$) before and after training.*

Time intervals in the most accommodated and disaccommodated states

In each cycle, we describe the time interval between reaching 90% of the total accommodation change and 10% of the disaccommodation change as the time interval in the most accommodated state. Similarly, the time interval in the most disaccommodated state is calculated from the time interval between reaching 90% of disaccommodation and 10% of accommodation. These intervals approximate to the times that the eye spends in “static” states between the main dynamic changes. One might expect these to have a value at least as long as the sum of the time taken to change the lenses (about 300 msec) and the accommodation reaction time (around 360 msec).

The means and standard errors of the time interval values at the accommodated and disaccommodated states at distance and near are shown in Table 8. Accommodative facility training had a significant impact on the time-interval values (ANOVA: $F1,_{2068}$= 32.3; p=0.0005).

Both before and after facility training, Analysis of variance showed a significant difference between the refractive groups with time interval for accommodation (pre-training: $F_{1,458}$= 4.94; p=0.027; post-training: $F_{1,588}$= 21.4; p=0.0005) but not for disaccommodation (pre-training: $F_{1,443}$= 0.11; p=0.735; post-training: $F_{1,576}$= 0.99; p=0.321).

		Interval of accommodation (s)	Interval of disaccommodation (s)
Pre -Training			
Emmetropes	Distance	1.14 ± 1.09	1.04 ± 0.90
	Near	1.50 ± 0.87	1.25 ± 1.08
Myopes	Distance	0.82 ± 0.70	1.37 ± 1.17
	Near	1.36 ± 1.52	0.86 ± 0.99
Post – Training			
Emmetropes	Distance	1.13 ± 0.61	0.90 ± 0.54
	Near	1.17 ± 1.10	0.91 ± 0.88
Myopes	Distance	0.78 ± 0.68	0.88 ± 0.65

	Near	0.90 ± 0.76	0.82 ± 0.83

Table 8: *Time intervals (seconds) spent in the accommodative and unaccommodative states before and after training. Results are shown for the two refractive groups and both distance and near testing.*

Discussion

Previous studies have shown that accommodative facility training improves the facility rate at distance and near, as measured both objectively and subjectively (Bobier & Sivak, 1982; Hung, Ciuffreda & Semmlow, 1986; Levine et al., 1985; Liu et al., 1979; Radhakrishnan et al., 2007; Randle & Murphy, 1974). The present study, using 15 minute training sessions on only 3 consecutive days, showed similar levels of improvement in accommodative facility rates in emmetropes and myopes, both at distance and near. Such improvements in accommodative facility were not evident in the control group, where measurements were taken on day 1 and day 5 with no facility training being given. Thus the improvements in facility observed with the main group of subjects were associated with the additional training that they had received, rather than simply being due to familiarity with the test procedure. An important aspect of this study was that the improvements in facility rates exhibited by the trained myopes and emmetropes were analysed further, using objective data, to investigate whether both refractive groups behaved in a similar manner following the accommodative facility training.

The improvements in accommodative facility rates following training could result from

- A reduction in the amplitude of the accommodative response during each accommodation and disaccommodation cycle

- A reduction in the time constants (time taken to reach the maximum level of accommodation or disaccommodation in each cycle (Bobier & Sivak, 1982; Liu et al., 1979)
- An improvement in velocity of accommodation or disaccommodation caused by changes in amplitude and/or time constant (Bobier & Sivak, 1982)
- A reduction in latency as a result of more efficient processing at a cortical level (Bobier & Sivak, 1982; Liu et al., 1979)

Following the period of accommodative facility training, measured objective amplitude of the accommodative response did not show any significant change for distance or near measurements. Any small changes were similar in magnitude to those found in previous studies (Bobier & Sivak, 1982; Liu et al., 1979). This indicates that the improvement in accommodative facility rates as a result of accommodative facility training is not due to a reduction in the accommodative response amplitude.

Pre-training objective amplitude values found in the present study were similar in magnitude to those found in Radhakrishnan et al. (2007), although the variation between subjects was considerably larger in the previous study when compared to the present study. This may explain why no significant differences between amplitudes of the emmetropes and myopes were found in the earlier study, whereas, significant differences were found between refractive groups in the present study, with amplitudes being larger in the myopes. The magnitude of this difference ranged up to over a dioptre in the near tests. A difference of up to 0.50D has been found as a result of diurnal variation in visually normal participants (Bobier & Sivak, 1982; Liu et al., 1979).

Accommodative training improved the time constants of accommodation and disaccommodation for both refractive groups during distance and near fixation. In the majority of cases, the time constants were reduced by a factor of about 1.6 as a result of the accommodative facility training. Liu et al. (1979) objectively assessed improvements in dynamic accommodation following accommodative facility training in patients who suffered from difficulties related to focusing at near. Their 3 subjects demonstrated high initial time constants which reduced substantially following training. Similarly, Bobier and Sivak (1982) showed an improvement in 'response time' following a period of 3-6 weeks of accommodative facility training in 5 subjects who initially showed slow accommodative responses.

The pre-training time constants for accommodation and disaccommodation were similar in magnitude to those found in our previous study (Radhakrishnan et al., 2007). Time constants for near were greater than time constants for distance. Kasthurirangan, Vilupuru & Glasser (2003) and Kasthurirangan & Glasser (2005) showed that time constants for accommodation increased linearly with the response amplitude, therefore it is not surprising that the time constants for near are larger than those for distance, given that the amplitude of response is higher in the near condition. The observed differences between distance and near may be due to the fact that the stimuli in the distance test lie within the operating ranges of retinotopic blur (approximately 1.50D), whereas the near accommodative target is more likely to be in the operating range for spatiotopic blur (>2.00D) (Schor, Alexander, Cormack & Stevenson, 1992; Seidel, Gray & Heron, 2003).

Prior to training myopes had longer time constants for accommodation and disaccommodation than emmetropes, with the difference being greater at distance than near fixation. The relatively high time constants in the myopic group are perhaps linked to the nature of the accommodative stimulus. Seidel et al. (2003) showed a deficit in retinotopic control of accommodation in myopes, leading to increased variability in the steady-state response and reduced performance in dynamic tasks. Although in our case both groups improved (time constants reduced) after training, the difference between the myopes and emmetropes persisted. The fact that the time constants in both refractive groups reduce by similar magnitudes post-training may indicate that facility training leads to a generalized improvement in time constants that is non-selective to the retinotopic and spatiotopic ranges. It is interesting that, as found in other studies (O'Leary & Allen, 2001; Pandian et al., 2006; Radhakrishnan et al., 2007), pre-training facility rates are systematically higher in emmetropes than myopes during distance testing (stimulus vergence range -0.17 to -2.10 D) but not during near testing (stimulus vergence range -0.50 to -4.32 D). This might suggest that the accommodation dynamics of different refractive groups vary in different ways across their amplitudes of accommodation, with myopes finding it more difficult to totally relax their accommodation, as required in the distance test.

Considering the various factors contributing to the differences in temporal response for different conditions and refractive groups, we note first that maximum velocities of accommodation and disaccommodation values improve considerably following facility training in both the refractive groups (Table 7). As maximum velocities are derived by dividing the amplitude by the time constant, if the amplitude does not change significantly after training the decrease in time constants with training leads to the improvement in velocities. This shows that the improvement in accommodative facility rates (as measured in clinical practice) in visually normal individuals following facility training results from a genuine increase in the velocity of accommodation and disaccommodation. These results indicate that the mechanisms of improvement in accommodative facility in visually normal subjects are similar to those found in patients with focusing difficulties at near (Bobier & Sivak, 1982; Liu et al., 1979).

Some previous work (Sterner, Abrahamsson & Sjostrom, 1999, 2001) has shown that patients with accommodative insufficiency demonstrate a marked improvement in accommodative facility rate and alleviation of symptoms following a period of facility training. The training period varied according to symptoms recorded every two weeks, with the training being stopped when the symptoms stopped. A similar protocol was used by Bobier and Sivak (1982) who trained their subjects for a period of 3 to 6 weeks, stopping when the facility rate reached 12 to 15cpm. Two of the 5 subjects returned for post-training measurements and the measurements made after 18 weeks of training cessation showed that the improvements in time characteristics were retained. In the present study, the subjects were trained over a 3 day period (days 2 to 4). All subjects were trained in the clinic for 15 minutes each day, with final measurements being taken on the fifth day. This ensured that all the subjects were compliant with the training regime and received the identical level of training. However, the current study had a relatively short training period and perhaps an extended training period would have still further increased the facility rates. We did not pursue the interesting question of how long the improved rates were sustained.

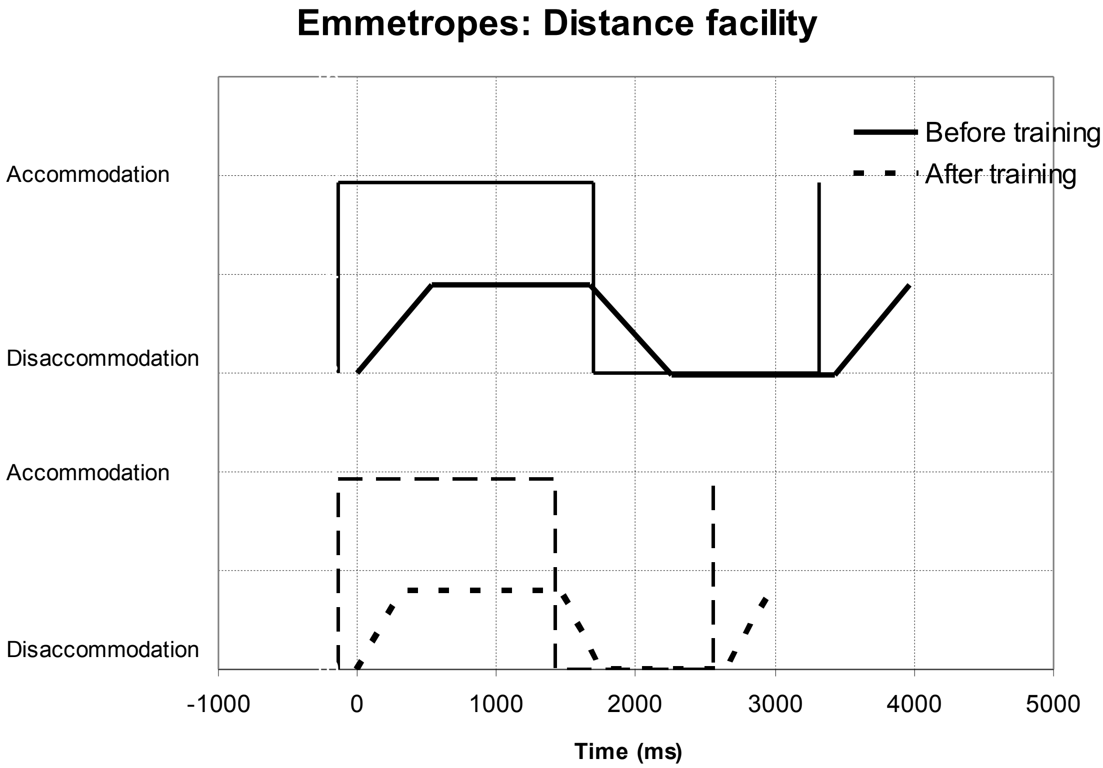
It was interesting to note the improvements in accommodative facility occurred in asymptomatic visually-normal participants and although the accommodative facility training was conducted only at a near fixation distance, post-training improvements were seen in both distance and near facility.

The initial, lower, distance accommodative facility rates appear to linked to accommodative dynamics. Previous work (Culhane & Winn, 1999; Schaeffel, Wilhelm & Zenner, 1993; Seidel et al., 2003) has shown that myopes exhibit abnormal accommodation dynamics and higher levels of near-work induced transient myopia (NITM) (Ciuffreda & Lee, 2002; Ciuffreda & Wallis, 1998; Hazel, Strang & Vera-Diaz, 2003; Vera-Diaz, Strang & Winn, 2002; Wolffsohn, Gilmartin, Li, Edwards, Chat, Lew & Yu, 2003). Accommodative facility training has been shown to improve NITM in young adult myopes (Ciuffreda & Ordinez, 1995). The findings of improved velocity and reduced time intervals in this study are in accordance with the improvements found in NITM with training (Ciuffreda & Ordinez, 1995).

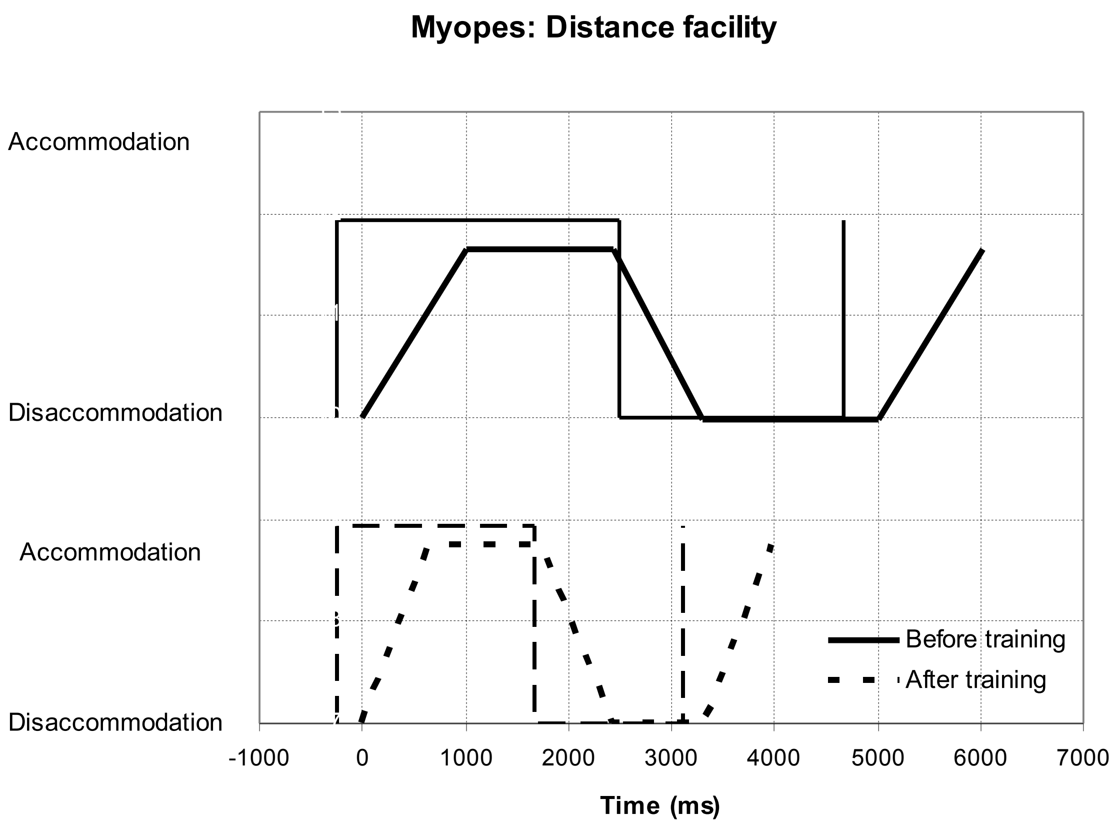
A new and important finding in the present data, however, is that the temporal differences between the behaviours of the emmetropic and myopic groups were accompanied by differences in the amplitudes of their accommodation changes. Somewhat surprisingly, the amplitudes were significantly larger in the myopic group, so that although the facility rate in the myopic group was lower than in the emmetropic group, the actual accommodative changes were higher and approximated more closely to the stimulus changes.

These differences in the overall responses are summarized schematically in Figure 2, which shows the basic form of the response changes over each cycle for the two subject groups and test distances. For simplicity, the response to each stimulus change is shown as varying linearly over a time interval which corresponds to that between t_{90} and t_{10} (i.e. ln9 X the time constant or 2.2τ). The vertical scale of the change in each schematic plot corresponds to the actual recorded response/stimulus change. Viewed in this way, it is apparent that the facility cycle becomes shorter in both myopes and emmetropes following training. As noted earlier, the improvement can be attributed to both an increase in the velocity of accommodation and disaccommodation and a reduction in time intervals. However it is clear that the higher facility rates of the emmetropes are achieved at the expense of less accurate accommodation responses. In general, it is well known that larger errors of accommodation may occur when accommodation is stimulated with negative lenses, as in facility training, rather than by changes in object distance (Abbott, Schmid & Strang, 1998; Gwiazda, Thorn, Bauer & Held, 1993).

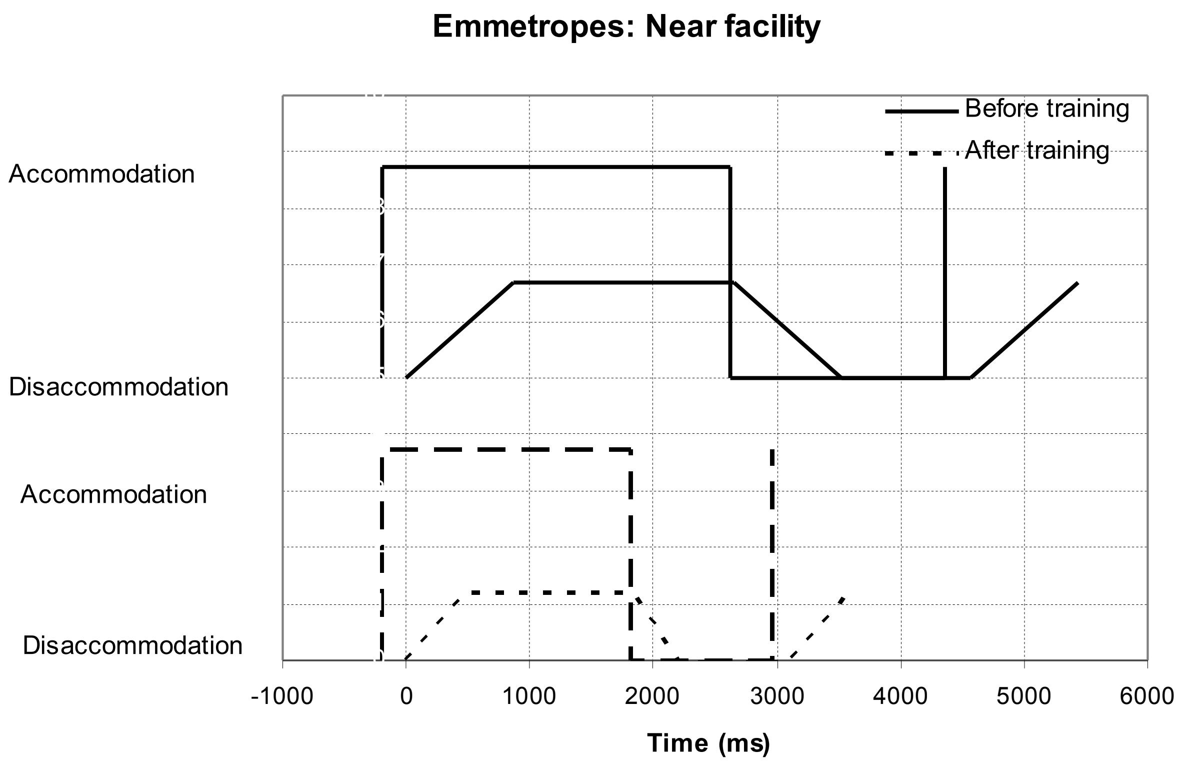
(a)


Emmetropes: Distance facility
Before training
After training
Accommodation
Disaccommodation
Accommodation
Disaccommodation
-1000
0
1000
2000
3000
4000
5000
Time (ms)

(b)


Myopes: Distance facility
Accommodation
Disaccommodation
Accommodation
Disaccommodation
Before training
After training
-1000
0
1000
2000
3000
4000
5000
6000
7000
Time (ms)

(c)


Emmetropes: Near facility
Before training
After training
Accommodation
Disaccommodation
Accommodation
Disaccommodation
-1000
0
1000
2000
3000
4000
5000
6000
Time (ms)

(d)

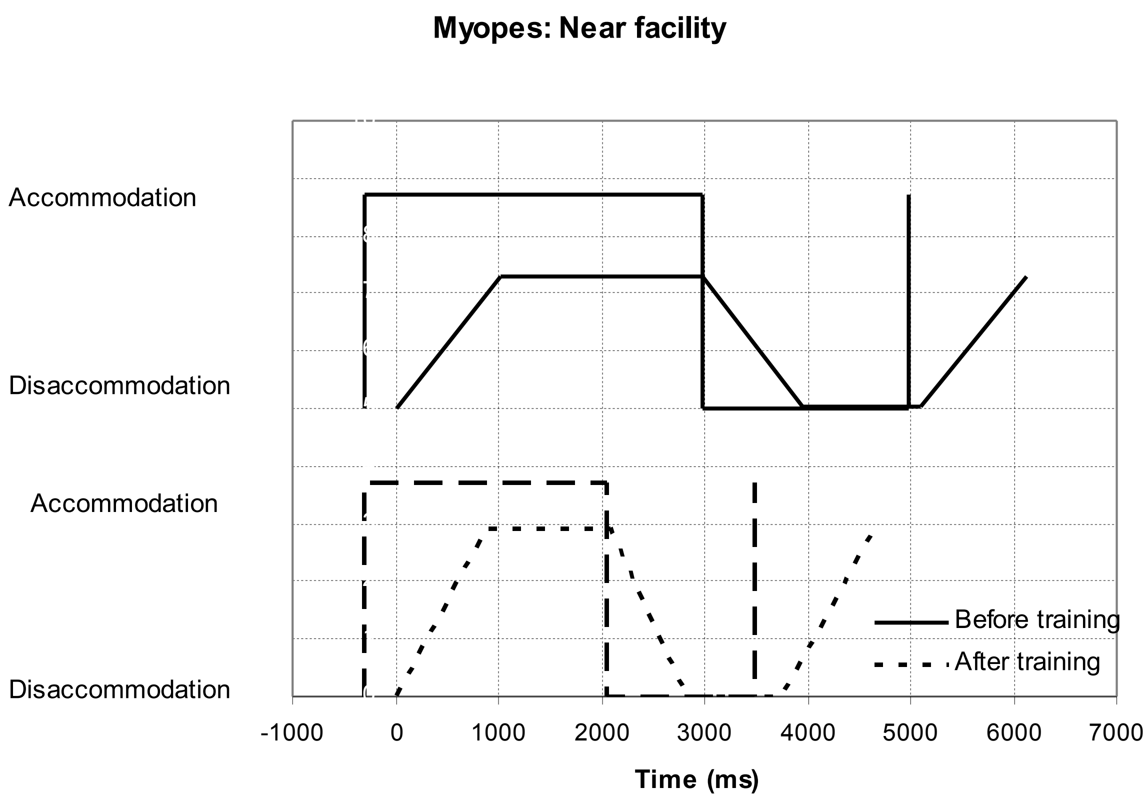

Myopes: Near facility
Accommodation
Disaccommodation
Accommodation
Disaccommodation
Before training
After training
-1000
0
1000
2000
3000
4000
5000
6000
7000
Time (ms)

Figure 2: *Schematic outline of mean changes in stimulus and response with time over one flipper cycle before and after training: horizontal lines are at 1D intervals. The stimulus change is 1.9 D for the distance test and 3.7 D for the near. Although the response amplitudes are shown correctly, for simplicity the responses are all shown as being accurate in the disaccommodated state, whereas in practice this may not be true. Results are shown for (a) emmetropes at distance; (b) myopes at distance; (c) emmetropes at near; (d) myopes at near. In each case the temporal changes in the stimulus are shown by a line changing abruptly between the accommodated and disaccommodated stimulus levels (see text). The corresponding response changes are shown schematically by the lines with sloping portions: the latter occur because, for simplicity, the responses are shown as changing linearly over the time intervals between t_{90} to t_{10} (see text). Note that for each condition myopes tend to taker longer to complete each cycle than emmetropes but that their amplitudes are larger. The durations of each flipper cycle are generally shorter after training than before training.*

It is, at first sight, surprising that the myopes produced higher amplitudes and hence more accurate responses than emmetropes, when it is generally assumed that the reverse is true (see, e.g. Rosenfield, 1998 for review). However, the more accurate responses often found for emmetropes are obtained under "steady-state" conditions when subjects are usually allowed as much time as they need to accommodate as accurately as possible. Facility testing involves dynamic conditions with an emphasis on the speed of response: the subject decides when the target is "clear" and actuates the lens changes. In fact our data suggest that using simple clinical measurements of subjective accommodative facility rates as an indicator of the relative efficiency of accommodation dynamics in individuals or groups may be misleading. It is not really true that the test can unambiguously evaluate the ability of the eye to alter accommodation rapidly and accurately. In practice the subject actuates the lens changes when he/she claims that the target is clear. There is no guarantee that different subjects have either the same criteria of clarity or that they react with the same motor speed to initiate the target change. Thus although the accommodative responses of our myopes were, in general, slower, their responses were more accurate than those of the emmetropes. To state that the myopes had inferior accommodation dynamics would, then, over-simplify the situation. In a repetitive task like that involved in facility testing, over-enthusiastic subjects may well use a combination of prediction and voluntary accommodation to accelerate the measured facility rate while paying only minor attention to the image clarity achieved.

If, then, accommodative facility measurements are to be made more reliable, there is a need to use an entirely objective method. Accommodation should be monitored on a continuous basis and the flipper-lens power should be changed automatically when the accommodation response reaches defined upper and lower criterion levels. Even then, interpretation of the results may be complicated by the differing importance to individual subjects of factors such as proximal and voluntary accommodation.

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