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## Accommodation to static chromatic simulations of blurred retinal images

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### Summary

The eye's longitudinal chromatic aberration (LCA) is known to drive 'reflex' accommodation to moving objects, but the evidence is not as clear for stationary objects. The present study examined whether accommodation can be driven by static simulations of the effects of defocus and LCA. Accommodation was recorded continuously while each of 12 subjects viewed images (through a 0.75 mm pinhole) that simulated the appearances of blurred sine wave gratings (3.9 c.p.d.). In two experimental conditions, an eye with normal LCA was assumed and defocus of +1 D or -1 D was simulated. In a control condition, an eye with neutralised LCA was assumed and target defocus of 1 D was simulated. Subjects' accommodation responses were consistent with the hypothesis that LCA provides a stimulus to accommodation. Chromatic aberration drives accommodation to both moving and stationary objects, and thus is an important stimulus for accommodation in everyday situations. The study findings are discussed in relation to colour vision, visual display terminals and emmetropization. © 1999 The College of Optometrists. Published by Elsevier Science Ltd. All rights reserved

### Introduction

Fincham (1951) was the first to demonstrate that the longitudinal chromatic aberration (LCA) of the eye could be important to the 'reflex' accommodative process. Commencing with some initial suggestions by Hartridge, Fincham hypothesised that colour fringes in the retinal image of a point object could provide a directional signal to the accommodation system. These colour fringes arise because short wavelengths are focused more myopically in the eye than long wavelengths. Thus, in an under-accommodated eye the retinal image of a white point object consists of a blue centre with a red fringe. In an over-accommodated eye the image consists of a red centre with a blue fringe. A red fringe would signal the need to increase accommodation, while a blue fringe would signal the need to relax accommodation. To test this hypothesis,

Fincham had subjects view test spots (3 minutes of arc) in either white or monochromatic light. About 60% of his subjects either focused poorly or not at all in monochromatic light, demonstrating that longitudinal chromatic aberration provides a stimulus to accommodation for a majority of subjects (Fincham, 1951). However, the results of later studies do not unanimously support Fincham's findings. One factor that appears to be important in this respect is the type of target motion used in a particular study. With a single exception, all studies using dynamic<sup>1</sup> target motion have demonstrated that longitudinal chromatic aberration provides a stimulus to accommodation, but most studies using stationary targets have concluded the opposite. Thus, there is disagreement on the issue of whether longitudinal chromatic aberration continues to provide a stimulus to accommodation when viewing a stationary object.

Recent studies have demonstrated that the accommodation response to dynamic targets is impaired in monochromatic light or when the longitudinal chromatic aberration of the eye is neutralised or reversed (Kruger and Pola, 1986; Kruger *et al.*, 1993, 1995b, 1997b; Aggarwala *et al.*, 1995a,b; Kotulak *et al.*, 1995). In one of these studies, subjects viewed a sinu-

<sup>1</sup>As used in this paper, the terms *dynamic* and *moving* will always refer to target motion towards and away from the eye, not lateral (left-right or up-down) target motion.

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soidally moving target (1.5–2.5 D at 0.2 Hz) either in monochromatic light, or in white light with the eye's normal longitudinal chromatic aberration intact, doubled, neutralised or reversed (Kruger *et al.*, 1993). Neutralising longitudinal chromatic aberration led to a diminished response, and reversing longitudinal chromatic aberration severely disrupted accommodation. Furthermore, this sensitivity to the effects of chromatic aberration is widespread: only a minority of subjects continue to focus well in monochromatic light (Kruger *et al.*, 1993; Kotulak *et al.*, 1995) or with longitudinal chromatic aberration neutralised (Kruger *et al.*, 1993). In another study, Kruger *et al.* (1995a) varied each of the red, green and blue components of a sine wave grating independently to simulate its appearance when oscillating from 1 D behind the retina to 1 D in front of the retina at 0.2 Hz. Subjects accommodated reasonably well to this dynamic simulation, leading Kruger *et al.* (1995a) to suggest that the relative contrasts of the short, middle and long wavelength components of the retinal image provide a directional stimulus to the accommodative system. Thus, except for the study of van der Wildt *et al.* (1974), which examined one subject in monochromatic light, the body of evidence suggests that longitudinal chromatic aberration provides an effective stimulus to accommodation when viewing dynamic targets.

Nevertheless, most studies suggest that chromatic aberration does not drive accommodation when the target of interest is stationary. Charman and Tucker (1978) found that the static accommodative stimulus–response function of one subject was not impaired in monochromatic light. More recently, Bobier *et al.* (1992) found that neutralising, increasing or reversing the eye's longitudinal chromatic aberration had no effect on the static accommodative stimulus–response function. Finally, Kotulak *et al.* (1995) found that the response to a stationary target at a 1 D stimulus level was independent of the spectral bandwidth of target illumination, and suggested that accommodation switches from chromatic to achromatic control when the temporal frequency content of target motion falls below about 0.2 Hz. In contrast, Kruger *et al.* (1997a) found that most subjects had poorer accommodation to a stationary target in monochromatic light or when the eye's longitudinal chromatic aberration was reversed. They suggested that some subjects may use voluntary accommodation to maintain a more accurate response to a stationary target when the normal stimulus provided by longitudinal chromatic aberration is absent.

While a previous study simulated sinusoidal changes in defocus (Kruger *et al.*, 1995a), the present study used steady targets to simulate stationary defocus in front of and behind the retina. The aim was to deter-

mine whether static simulations of the effects of defocus and longitudinal chromatic aberration are sufficient to drive accommodation in the absence of feedback.

## Methods

### Subjects

Thirteen subjects were recruited for the study, but one was excluded due to accommodative spasm when viewing targets through the 0.75 mm pinhole pupil. Thus, 12 subjects participated in the study. They were optometry students, staff of the College, or members of the public. Six of the subjects were unaware of the purpose of the study. Authors JHL and LRS served as subjects 6 and 11 respectively. All subjects gave informed consent to participation in the experiment. The study was approved by the Institutional Review Board of the College, and followed the tenets of the Declaration of Helsinki.

Subjects' ages ranged between 16 and 30 years. All were visually normal and had no history of amblyopia, strabismus, or significant ocular injury or ocular disease. In the right eye, equivalent ocular spheres ranged between +0.34 and –5.25 D, with ocular cylinders ranging up to –1.01 D. In the left eye, equivalent spheres ranged between +0.59 and –5.46 D with cylinders ranging up to –1.69 D. The degree of ocular anisometropia ranged between 0 and 0.94 D. Right and left eye best corrected visual acuities ranged from  $6/3^{-2}$  to  $6/7.5$  and  $6/3.8^{+1}$  to  $6/6^{-2}$  respectively. Ocular amplitudes of accommodation for the right and left eyes varied in the ranges 5.03–11.79 D and 5.25–11.79 D respectively. Three subjects had amplitudes below Duane's (1922) clinical norms by 0.9–2.3 D, but were asymptomatic. Dark focus of accommodation varied in the range 0.04–3.50 D with a mean of 1.47 D. All subjects had normal colour vision in both eyes by Farnsworth D15 panel and Nagel Anomaloscope.

### Apparatus

The apparatus included an infra-red recording optometer and associated Badal optical system (Kruger, 1979; Kruger *et al.*, 1993), a Sharp XGE-800U liquid crystal display (LCD) video projector, and a Draper (Spiceland, Indiana) 'Mini Cine' projection screen.

The infra-red optometer monitored dynamic changes of accommodation along the vertical meridian of the eye at a sample rate of 100 Hz (Kruger, 1979). The relationship between accommodative response and optometer output is linear over a 6 D range. The optometer is insensitive to pupil size provided that the pupil diameter is 3 mm or larger. It is also insensitive

to eye movements within  $\pm 2^\circ$  of central fixation. The noise level (standard deviation) with a Bausch and Lomb schematic eye is 0.029 D. Subjects were positioned in front of the optometer with a dental bite plate and headrest. Eye position was monitored by the examiner using an infra-red video camera and video monitor.

A modified Badal optometer was used to present targets to the subject (Kruger *et al.*, 1993). This optometer allows an artificial pupil to be imaged in the subject's real pupil plane. Specially designed lenses can be introduced at the artificial pupil plane of the Badal optical system to reverse or neutralise the longitudinal chromatic aberration of the eye, as necessary (Kruger *et al.*, 1993). The system is also versatile regarding target presentation, and in this study two types of targets were used: a back-illuminated 35 mm photographic transparency of a Maltese cross seen in Maxwellian view (Westheimer, 1966), and computer generated images projected onto a screen and seen in non-Maxwellian view. The accommodative stimulus provided by the target was varied using a motorised prism which moved along the light path of the optical system (Kruger *et al.*, 1993). Refractive errors were approximately corrected with spectacle lenses or the subject's own contact lenses. In the latter case, trial runs were made to ensure that stable optometer readings could be obtained with the contact lens. The computer program that controlled the motorised prism took into account the subject's ocular refraction (or contact lens ocular over-refraction), the lenses in place at the spectacle plane, and the vertex distance of these lenses. Thus, regardless of the subject's refractive error or the lenses in place, correct accommodative stimuli were always provided by the optometer to within the usual precision of subjective refraction; that is, about  $\pm 0.3$  D (Rosenfield and Chiu, 1995). The field stop of the optometer provided an  $11.2^\circ$  field of view. The edges of the field stop were blurred by about 5.2 D beyond the far point of an emmetrope or corrected ametropes, and thus, due to their eccentricity and blurred detail, did not provide a stimulus to accommodation.

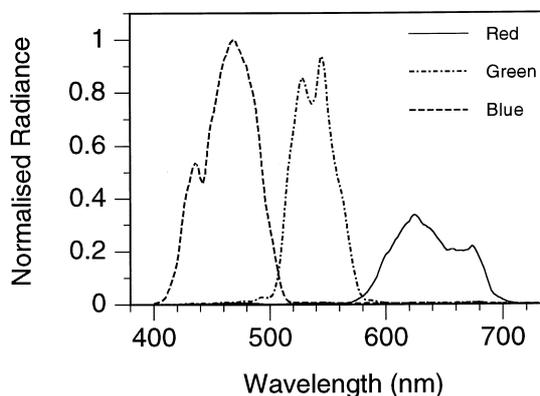
The Sharp XGE-800U video projector displayed images from a Power Macintosh 8100/80 computer. The luminance profile of the projector was gamma corrected in software to give approximately a linear relationship between image grey level (256 levels) and screen luminance. The maximum departure from linearity was 4.9% of the useable luminance range. After gamma correction, there were small differences in the maximum Michelson contrasts available from the individual LCD panels: these were 0.82, 0.75 and 0.71 for red, green and blue panels respectively. Luminances provided by the individual red, green and blue panels were independent of each other to within 8.5%. The

LCD panels were aligned by a Sharp technician before commencing the study.

### Stimulus

Peak radiances for the red, green and blue LCD panels of the Sharp video projector were at 624, 544 and 470 nm respectively (*Figure 1*). The spectral bandwidths at half height for the red, green and blue LCD panels were 84, 44 and 60 nm respectively (*Figure 1*). When weighted by the photopic spectral luminous efficiency function ( $V_\lambda$ ), these bandwidths are 44, 40 and 42 nm respectively. The bandwidths are reasonably narrow, and later calculations assume that the three LCD panels are monochromatic. This assumption would tend to dampen slightly the effectiveness of the simulations. Chromatic differences of refraction between the long (624 nm), middle (544 nm) and short (470 nm) wavelengths were calculated using the Chromatic Eye of Thibos *et al.* (1992), which accurately models the longitudinal chromatic aberration of the adult human eye. The eye was taken to be emmetropic for 544 nm, the wavelength at which the green LCD panel of the Sharp projector has its peak radiance. The dioptric difference between wavelengths was 0.37 D for the red and green panels, and 0.56 D for the green and blue panels.

The simulations used in this study were created from a vertical black-and-white sine wave grating that had a Michelson contrast of 75.6% and a spatial frequency of 3.88 cycles per degree. Targets at this spatial frequency provide a good stimulus to accommodation (Mathews and Kruger, 1994). Our aim was to simulate the retinal image of the grating when viewed with a 3 mm pupil and defocused by either +1 or -1 D with respect to the retina. In this paper, following standard clinical conventions, positive defocus will refer to



**Figure 1.** Normalised radiance profiles for the red, green and blue LCD panels of the Sharp XGE-800U video projector.

**Table 1.** Defocus, modulation and contrast values for the three sine wave grating simulation patterns

Condition	LCD panel	Defocus (D)	Modulation	Contrast <sup>a</sup>
Positive	Red	+1.38	0.27	0.22
	Green	+1.00	0.54	0.41
	Blue	+0.45	0.90	0.64
Negative	Red	-0.63	0.80	0.65
	Green	-1.00	0.54	0.41
	Blue	-1.56	0.15	0.11
Control	Red	1.00	0.54	0.44
	Green	1.00	0.54	0.41
	Blue	1.00	0.54	0.38

<sup>a</sup>For these patterns, Michelson contrast = Modulation  $\times$  In-focus contrast, where the in-focus contrasts were 0.82, 0.75 and 0.71 for red, green and blue image components respectively

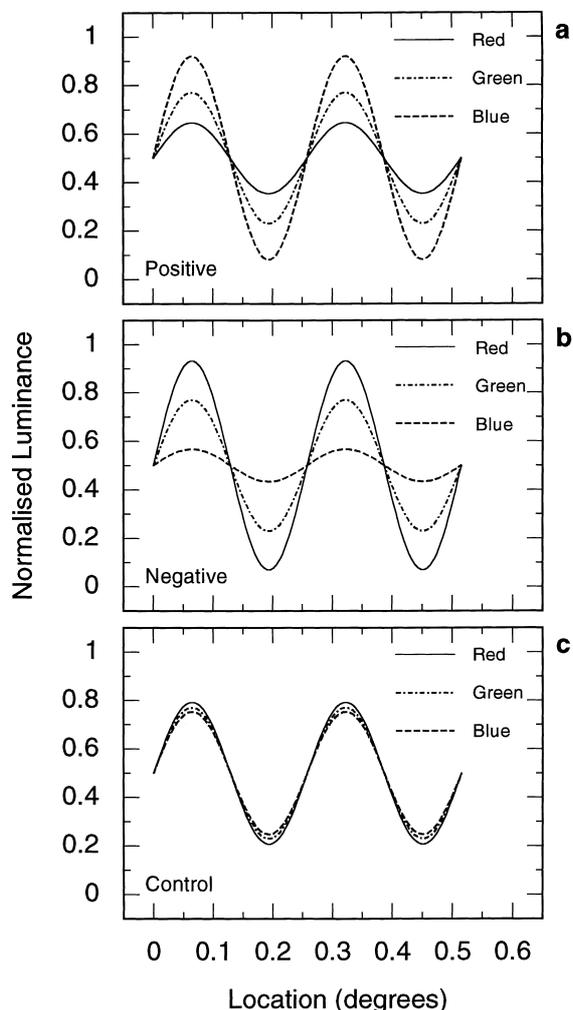
hyperopic defocus; that is, light focused behind the retina. Negative defocus will refer to myopic defocus; that is, light focused in front of the retina.

It was assumed that aberrations other than chromatic aberration are negligible for a 3 mm pupil. At this pupil size and for a grating spatial frequency of 3.9 c.p.d., the monochromatic aberrations of the eye have negligible effects on the in-focus modulation transfer function (MTF) and phase transfer function (Walsh and Charman, 1985; Liang and Williams, 1997). In addition, the monochromatic aberrations, considered collectively, do not vary greatly with accommodative level (Atchison *et al.*, 1995). For a 3 mm pupil, there may be focus dependent shifts in grating phase due to monochromatic aberrations (Walsh and Charman, 1989), but these phase shifts were not modelled in the simulations used in the present study.

It is important to note that all grating simulations were viewed through a pinhole pupil (0.75 mm) which was aligned on the 'visual axis' of the eye (Thibos *et al.*, 1990) and imaged at the plane of the eye's entrance pupil. The large depth of focus provided by the pinhole pupil ensured that the contrast and chromatic content of the simulations were only minimally influenced by defocus due to either accommodation or the eye's natural longitudinal chromatic aberration (Appendix).

There were three experimental conditions: a positive, a negative and a control condition. The positive and negative conditions assumed intact longitudinal chromatic aberration in the eye, while the control condition simulated an eye in which longitudinal chromatic aberration had been neutralised. The positive condition represented a sine wave grating defocused by 1 D behind the retina. This simulated hyperopic defocus in

which the short wavelengths were focused closer to the retina than the long wavelengths. In this condition, the short wavelengths had higher contrast than the long wavelengths (Table 1, Figure 2). The positive condition should signal the eye to increase focus. The negative condition represented a sine wave grating defocused by 1 D in front of the retina. This simulated myopic focus in which the long wavelengths of the retinal image were focused closer to the retina than the short wavelengths. In this condition, the long wavelengths of the grating simulation had higher contrast than the short wavelengths (Table 1, Figure 2). The negative condition should signal the eye to relax focus. The control condition represented a sine wave grating defocused by

**Figure 2.** Theoretical normalised luminance profiles of the sine grating patterns for the positive condition (a), the negative condition (b) and the control condition (c).

1 D for long, middle and short wavelengths. The long, middle and short wavelengths had similar contrasts in the control condition (Table 1, Figure 2) and, if anything, specified a slight reduction in focus. The small differences in the red, green and blue contrasts in the control condition result from slightly different gamma functions for the respective LCD panels.

The required contrasts of red, green and blue image components were calculated for each condition using Smith's (1982) geometrical optical modulation transfer function (Table 1). The demodulated red, green and blue components of the sine wave were then combined to form the final composite 'black-and-white' sine wave grating. Examples of the theoretical normalised luminance profiles of the gratings for positive, negative and control conditions are shown in Figure 2.

The mean space averaged retinal illuminance provided by all three simulation patterns was 21 trolands. Each pixel in the patterns subtended approximately 1.93 minutes of arc at the eye. The nominal spatial frequency of the gratings was 3.88 c.p.d., but the actual spatial frequencies varied in the range 3.79–4.45 c.p.d. due to spectacle magnification induced by correcting lenses placed in front of the eye.

### Procedures

In a preliminary session, a case history was gathered, colour vision was tested, and subjective refraction, visual acuity and amplitude of accommodation were measured. In the main session, trial lenses were placed in front of the left eye to correct approximately any refractive error, and the right eye was patched.

The subject was positioned in the apparatus and moved horizontally so that the visual axis, as operationally defined by Thibos *et al.* (1990), was aligned with the optical axis of the Badal stimulus system. There was no horizontal transverse chromatic aberration (TCA) for foveal viewing at this position. During the alignment procedure (Thibos *et al.*, 1990), the subject viewed two vertical vernier lines through the 0.75 mm pinhole pupil of the Badal optical system. The upper line was red (Kodak Wratten filter No. 92; dominant wavelength, 645 nm) and the lower line was blue (Kodak Wratten filter No. 47; dominant wavelength, 464 nm). The subject's task was to position her head using the horizontal alignment dial of the bite plate stage so that the two coloured lines appeared to be vertically aligned. The position of the eye was then noted by the examiner, and the subject was aligned on this visual axis throughout the rest of the experiment. (Subject 1 was inadvertently misaligned by 0.25 mm.)

To calibrate the infra-red optometer, the subject viewed a Maltese cross target (Kruger and Pola, 1986) at a number of different accommodative stimulus levels

(for example, 0, 1, 2, 3 and 4 D) while simultaneous measurements of subjective focus and optometer output were made. To measure subjective focus at each target distance, we developed a novel technique called bichromatic stigmatoscopy. The bichromatic stigmatoscope is mounted in the Badal system, and the stigmatoscope target is optically superimposed over the Maltese cross using a pellicle beam splitter. The stigmatoscope target is a thin horizontal slit in an aluminium sheet, back illuminated by a halogen light source. The slit is covered on the left side by a blue-green filter (500 nm) and on the right side by a red filter (642 nm). In the Chromatic Eye (Thibos *et al.*, 1992) there is a 0.73 D difference in refractive error between the two filters, and a wavelength of 557 nm corresponds to the refractive error midway between the refractive errors for the two filters. The stigmatoscope target was oriented horizontally to measure refraction along the vertical meridian of the eye, the same meridian as used by the infra-red optometer. The subject adjusted the vergence of the stigmatoscope target by rotating a remote control device that moved the target back and forth along the optical axis of the Badal system. At each target distance, the subject was instructed to look at the limb of the Maltese cross and to adjust the remote control device so that the red and blue-green lines appeared equally blurred. A measurement was then taken with the infra-red optometer. Accommodative response values were calculated from the stigmatoscope target position, and principal axis regression (Sokal and Rohlf, 1981) was used to obtain a linear equation relating accommodative response (D) to infra-red optometer output (V).

Following calibration, the subject's accommodation responses to dynamic targets were examined. These preliminary trials were used to determine the degree to which subjects use longitudinal chromatic aberration under dynamic stimulus conditions. The subject viewed a Maltese cross (Kruger and Pola, 1986) moving sinusoidally between 1 and 3 D at a temporal frequency of 0.195 Hz under three conditions: (1) in white light with normal longitudinal chromatic aberration intact, (2) in white light with the eye's longitudinal chromatic aberration reversed using a specially designed lens (Kruger *et al.*, 1993), and (3) in monochromatic light (550 nm, 10 nm bandwidth). Each trial lasted 40.96 sec, and the target was viewed through a 3 mm artificial pupil.

The subject then sat in complete darkness for 3 min so that accommodative adaptation effects might subside (Rosenfield *et al.*, 1994), and a 30 sec recording was made with the infra-red optometer to determine the subject's dark focus.

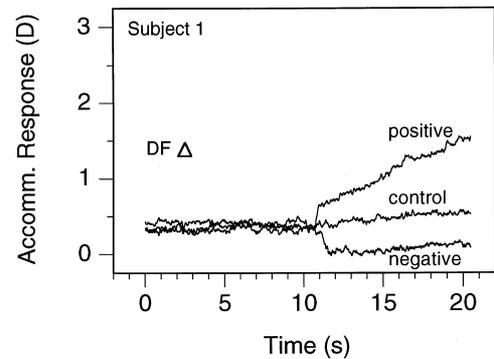
In the main part of the experiment, the subject viewed the grating simulations through a 0.75 mm pinhole pupil. This pinhole 'opens' the negative feedback

loop of the accommodation system by providing a large depth of focus such that any changes in accommodation have little or no effect on retinal image contrast (Appendix). In each trial, the subject viewed a 20.48 sec video presentation consisting of two parts of equal length. During the first 10.24 sec of the trial, the target was a fixation cross (3.87 minutes of arc limb width) of low contrast (9.1%) on a mid-grey background (25 trolands). During the last 10.24 sec of the trial, the cross was replaced by one of the three sine wave grating simulations: whether positive, negative or control condition simulation. The order of presentation of the three conditions was counterbalanced (Namboodiri, 1972), and there were six trials of each condition. Subjects were instructed to 'concentrate on the centre of the target and keep the target clear.' The subject was also instructed to change fixation between the dark and light bars of the grating targets to the beat of a metronome (0.33 Hz) so as to reduce the possibility of after-images and perceptual fading. The following requests were made of the subject at the end of the experiment: 'Describe what you saw in the experiments' and 'Describe the colours that you saw'.

#### Analysis

Blinks were manually edited from the accommodation records before analysis, and replaced with a linear interpolation between the pre- and post-blink points. Trials were excluded from analysis if they contained more than 12% of blink affected data. (This criterion was not applied to the dark focus trials.) For accommodation responses to the dynamic (sinusoidally moving) targets in the preliminary trials, gains and phases were calculated using a Fast Fourier Transform (FFT). To reduce spectral leakage in the FFT, the mean and linear trend were subtracted from the data before analysis and a Hamming window was applied. Gain is the amplitude of the response divided by the stimulus amplitude. Phase lag is the distance in degrees from the peak of the sinusoidal response to the peak of the sinusoidal stimulus.

For the main trials involving the sine wave grating simulations, mean accommodative responses were calculated for the first 10.24 sec of each trial (fixation cross) and the last 10.24 sec of each trial (sine grating simulation). Then the change in mean accommodative response from the cross to the grating ( $\Delta$ ) was calculated and used as the main parameter in all later analyses. This procedure was necessary because open loop responses typically vary a great deal from trial to trial, and thus a simple comparison of mean responses to the positive, negative and control condition simulations would not be sufficiently sensitive from a statistical viewpoint. Thus, the response to the cross was



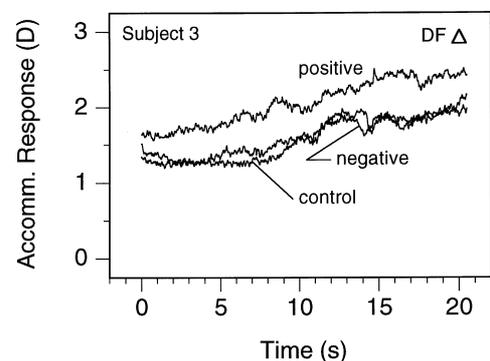
**Figure 3.** Mean accommodation response ( $n=6$  per condition) as a function of time for Subject 1 in the positive, negative and control conditions. DF is the dark focus level.

used as an individual control in each trial to determine more precisely the direction in which the grating simulations drove accommodation.

#### Results

For the main trials, two representative response patterns are plotted (*Figures 3 and 4*). One subject demonstrated a strong response to the stimuli (*Figure 3*), while the other subject responded weakly to the stimuli (*Figure 4*). In the case of Subject 1, the negative condition led to a lower response than the control condition, whereas the positive condition led to a higher response than the control condition (*Figure 3*). It is also likely that the response in the negative condition would have been even more pronounced if the subject had not been prevented from focusing further by the far point of accommodation.

When interpreting these and later figures, it is important that all responses be considered in relation to those for the control condition: interpretations based on absolute changes in accommodation to the positive



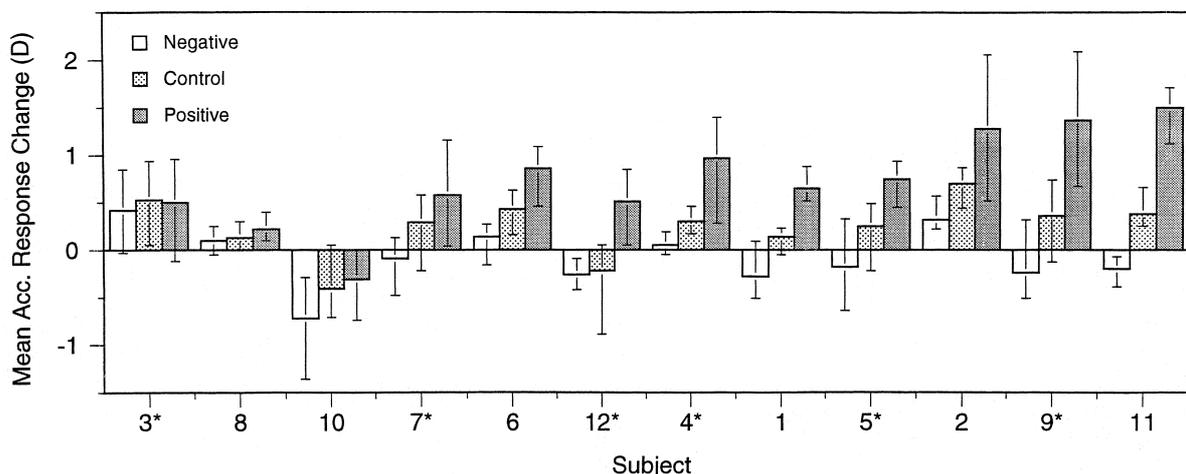
**Figure 4.** Mean accommodation response ( $n=6$  per condition) as a function of time for Subject 3 in the positive, negative and control conditions. DF is the dark focus level.

and negative conditions will be misleading. This is because the experiment was conducted with a pinhole pupil, allowing accommodation to drift over a large range with little change in target contrast. This tonic accommodative state is susceptible to several factors including perceived distance (Rosenfield *et al.*, 1991), mental imagery (Malmstrom and Randle, 1976) and cognition (Winn *et al.*, 1991), and exhibits drifts at low temporal frequencies (Gray *et al.*, 1993) which become more prominent at higher accommodative levels (Stark and Atchison, 1997). Thus, any response to the chromatic content of the grating target is superimposed over a labile tonic accommodative state which can be influenced by a number of factors. For example, if a subject's open loop accommodative level tends to drift inwards over the course of a 20 sec trial (e.g., Figure 4), then it may be impossible to show an absolute reduction in accommodation to the negative condition grating, even though the target does lead to a relative reduction in accommodation when compared with the control condition. Conversely, an absolute outward shift of accommodation to a grating target would not necessarily imply that the target provided a direct stimulus to reduce accommodation: possibly the subject's tonic accommodative state drifted outward. Thus, to gain meaningful conclusions from the results, the control condition must be used as a standard against which the positive and negative conditions are compared.

The mean accommodation response changes ( $\Delta$ ) for each subject and condition are shown in Figure 5. First, consider the accommodative responses in the control condition, where the effects of LCA were close

to absent. Ten of 12 subjects focussed inwards over the course of the trial, and so any accommodative changes in the positive and negative conditions must be considered in relation to this baseline drift in the control condition. Most subjects responded in the correct direction in the positive and negative conditions. That is, the positive condition simulated hyperopic defocus, or a lag of accommodation, and signalled the eye to increase accommodation relative to the control condition. The negative condition simulated myopic defocus, or a lead of accommodation, and signalled the eye to relax accommodation relative to the control condition. For most subjects there is a definite ordering of the three responses in the direction that would be predicted if longitudinal chromatic aberration provides a stimulus to accommodation. A repeated measures ANOVA and *post-hoc* Scheffé tests were performed with the data. These tests revealed: (1) a significant overall effect of simulation type (ANOVA:  $F = 30.26$ ,  $p = 0.0001$ ), (2) a significantly higher response in the positive than the negative condition (Scheffé:  $F = 29.76$ ,  $p \ll 0.0001$ ), (3) a significantly higher response in the positive than the control condition (Scheffé:  $F = 11.15$ ,  $p = 0.00046$ ), and (4) a significantly lower response in the negative than the control condition (Scheffé:  $F = 4.47$ ,  $p = 0.024$ ). All these significant differences were in the direction that would be predicted if longitudinal chromatic aberration provides a stimulus to accommodation.

Subjects were asked to describe any colours they saw in the patterns. Inadvertently, the responses of one subject (Subject 1) were not recorded, but of the remaining 11 subjects, three (Subjects 4, 5 and 7) did



**Figure 5.** Mean change in accommodation response for the positive, negative and control conditions. Subjects are arranged in ascending order by the size of the difference between positive and negative condition values. Error bars denote the range of observed values. An asterisk (\*) denotes a subject naive to the purpose of the study.

not see any colours, seven subjects (Subjects 2, 3, 6, 8, 9, 10 and 12) described the colours they saw but did not provide any details of the spatial arrangement of those colours, while one subject (Subject 11) gave a definite description of the coloured patterns. Subject 11 noted that the troughs of the sine gratings appeared either blue or red. The Robust Rank Order test (Siegel and Castellan, 1988) was used to determine if the subjects who saw colours also responded most strongly to the simulations. Subjects were divided into two groups: those who saw colours ( $n = 8$ ), and those who did not ( $n = 3$ ). The difference in mean accommodation response change ( $\Delta$ ) between the positive and negative conditions was used as a measure of the strength of the response to the simulations. There was no evidence for a relationship between the strength of the response and the perception of colours (Robust Rank Order:  $\hat{U} = 0.43$ ,  $p > 0.1$ ); nevertheless, the analysis is limited because there were only three subjects in the group who did not report seeing colours.

All subjects viewing the dynamic targets (0.2 Hz) performed better with normal longitudinal chromatic aberration intact than in the monochromatic or reversed longitudinal chromatic aberration conditions. Ratios for reversed condition gain to normal condition gain and monochromatic condition gain to normal condition gain were calculated for each subject. Reversed-normal gain ratios ranged between 0.07 and 0.74 with a mean of 0.32, and monochromatic-normal gain ratios ranged between 0.30 and 0.97 with a mean of 0.64. These ratios were significantly different from 1.00 indicating that accommodation is impaired in monochromatic light and when longitudinal chromatic aberration is reversed (One tailed  $t$ -test; reversed *vs.* normal;  $n = 9$ ,  $t = -9.7$ ,  $p \ll 0.0001$  monochromatic *vs.* normal;  $n = 10$ ,  $t = -4.61$ ,  $p = 0.0006$ ). These results for moving targets concur with previous findings (Kruger *et al.*, 1993).

Responses to the dynamic targets (0.2 Hz) were compared with those for the static simulations using principal axis regression (Sokal and Rohlf, 1981). For the dynamic targets, the ratio of accommodative response gain in the reversed LCA condition to that in the normal LCA condition ( $RvN$ ) was used as a measure of a subject's sensitivity to LCA; a low value indicating sensitivity to LCA. For the static simulations, the difference in mean accommodative response change ( $\Delta$ ) between the positive and negative conditions was used as a measure of the response strength ( $RS$ ); a high value indicating sensitivity to LCA. There was an inverse correlation between these two measures, demonstrating that subjects who focused poorly to the static simulations (indicating a lack of sensitivity to LCA) also focused reasonably well in the dynamic condition with their normal LCA

reversed (again, indicating a lack of sensitivity to LCA). However, the slope of the best fit line was not significantly different from zero ( $RS = -4.1 RvN + 2.2$ ,  $r^2 = 0.29$ ,  $p = 0.13$ ).

## Discussion

The present results demonstrate that most subjects do respond to the chromatic stimulus provided by static simulations of the effects of defocus and longitudinal chromatic aberration. This provides further evidence that the chromatic stimulus to accommodation operates for both stationary and moving targets, and the findings agree with those of a previous study that used stationary targets and a 3 mm pupil (Kruger *et al.*, 1997a). Everyday tasks such as reading a book or viewing a computer monitor require focus for a stationary target, and the results of the present study suggest that chromatic aberration drives accommodation in these situations.

The present results are in contrast to those of other studies that found no reduction in accommodation accuracy for stationary targets when the eye's longitudinal chromatic aberration was reversed, doubled or neutralised (Bobier *et al.*, 1992), or when the spectral bandwidth of target illumination was reduced (Charman and Tucker, 1978; Kotulak *et al.*, 1995). With stationary targets, subjects may use voluntary accommodation to obtain a better subjective focus, even though this is difficult for some in monochromatic light or when the eye's longitudinal chromatic aberration is neutralised or reversed (Kruger *et al.*, 1997a). These difficulties are manifested as larger than normal fluctuations of accommodation or sudden loss of focus (Kruger *et al.*, 1997a), and are best detected with a continuously recording optometer. Kotulak *et al.* (1995) used a stationary target at a stimulus level of 1 D and found that the spectral bandwidth of target illumination had no effect on accommodation. A possible explanation for this finding is that a target distance of 1 D is close to the accommodation resting level of many subjects: approximately 1.5 D on average (Leibowitz and Owens, 1978). Little effort is needed to focus at a distance close to the resting level, and this may be why spectral bandwidth had no effect on the accuracy of accommodation (Kruger *et al.*, 1997a).

It may be argued that subjects saw colours in the grating patterns and then made voluntary accommodation changes to the coloured patterns. This hypothesis was not supported by a statistical test that compared the responses of subjects who saw colours and those who did not. At the spatial frequency of the present grating simulations (3.9 c.p.d.), colour differences between the peaks and troughs of the gratings

are probably close to the threshold for colour naming (Kruger *et al.*, 1995a). Most subjects were vague in their descriptions of the colours they saw, simply listing various colours but not describing where those colours appeared in the patterns. Also, because the simulations were viewed through a pinhole pupil to eliminate the effects of blur, it was not possible for subjects to learn associations between their accommodation responses and any subtle colour changes in the targets due to defocus.

An explanation for the results based on slight differences in overall 'blur' or contrast is unlikely. Michelson luminance contrasts for the positive, negative and control simulations were 0.415, 0.401 and 0.411 respectively. Differences in contrast do not exceed 1.4%, and are too small to explain the pattern of responses observed in this study.

Explanations for the results based on the labile nature of the open loop accommodative state are unlikely. Any low temporal frequency drifts in the open loop response (Gray *et al.*, 1993) were small enough to allow statistically significant differences to be observed between the three experimental conditions. Most subjects did not verbally differentiate between the three grating targets, and so systematic differences in perceived distance (Rosenfield *et al.*, 1991), mental imagery (Malmstrom and Randle, 1976) or cognition (Winn *et al.*, 1991) between the various simulations are unlikely to explain the results.

Finally, some methodological factors can be ruled out. Because the target did not step in position, small lateral shifts of the target or changes in target size (Troelstra *et al.*, 1964) could not act as cues to accommodation. Mean retinal illuminance was identical in the three conditions (Troelstra *et al.*, 1964). The order of target presentation was counterbalanced (Troelstra *et al.*, 1964). There were no auditory cues available (Allen, 1955). Transverse chromatic aberration is unlikely to have provided a cue because subjects were aligned on the visual axis (Thibos *et al.*, 1990), ensuring zero horizontal TCA for foveal viewing. The pinhole pupil would have significantly reduced the effectiveness of contrast-maximising mechanisms such as voluntary trial-and-error focus changes or a mechanism based on accommodative fluctuations (Kotulak and Schor, 1986). Indeed, such mechanisms would tend to produce similar (rather than different) responses in the three conditions. Focus dependent shifts in spatial phase due to spurious resolution (Smith, 1982) can be ruled out based on the range of accommodative levels in the experiment and the MTF for a 0.75 mm pupil (Appendix). Focus dependent shifts in phase due to ocular aberrations (Walsh and Charman, 1989) are probably negligible for a 0.75 mm pupil at 3.9 c.p.d.

When viewing a dynamic target, all subjects in this study performed better with normal longitudinal chromatic aberration than in monochromatic light or with their longitudinal chromatic aberration reversed. Subjects clearly use the chromatic cues available in white light to follow the sinusoidally moving target. In monochromatic light (550 nm), subjects had reduced gain but were still able to respond. Responses in this condition may depend on other achromatic stimuli, as yet undiscovered (Kruger *et al.*, 1997b).

The comparison between static and dynamic responses suggested a correlation between the two responses. Subjects who responded poorly to the static simulations tended to respond well under dynamic conditions when their LCA was reversed, suggesting an insensitivity to LCA in both static and dynamic conditions. However, this tendency was not statistically significant. Thus, there is not a firm correlation between the responses in the two conditions. One reason may be that the only chromatic information available to accommodation in the static trials with a pinhole pupil was from differences in cone contrasts (e.g., L- vs. M-cone contrast). However, in the dynamic trials with a 3 mm pupil there was also the potential for different cone classes to sample the light vergence directly, perhaps by a Stiles-Crawford type mechanism. In addition, there may be differences in responsiveness under static and dynamic conditions.

Over the last decade a body of literature has accumulated that clearly demonstrates the importance of chromatic aberration to reflex accommodation for both stationary and moving targets. In the remainder of this discussion we consider several clinical and practical applications of the chromatic stimulus to accommodation, and make suggestions for further research.

#### *Accommodation and colour deficiency*

There has been little research on the effects of colour vision deficiencies on accommodation (Fincham, 1953; Heath, 1956; Kruger *et al.*, 1993; Kotulak *et al.*, 1995). In the most extensive of these studies, Fincham (1953) found that colour normal subjects had better accommodation responses to spot targets in heterochromatic light than in monochromatic light, indicating that chromatic aberration was providing a stimulus to accommodation in heterochromatic light. Two anomalous trichromatic subjects (one deuteranomalous, one protanomalous) showed patterns similar to those of the colour normals. However, two other studies have reported that two deuteranomalous subjects continue to focus well in monochromatic light (Kruger *et al.*, 1993; Kotulak *et al.*, 1995). Fincham also found that three of five protanopic subjects and four of 10 deuteranopic subjects showed no accommodation responses

to the largest spot target ( $1^\circ$ ). The eight dichromatic subjects who did respond to the targets showed no improvement from monochromatic to heterochromatic light, indicating the lack of a chromatic stimulus to accommodation. Fincham's (1953) study raises two issues. Firstly, what mechanism is being used by the dichromatic observer to accommodate in monochromatic light? One suggestion is that an asymmetric Stiles-Crawford function may be used by foveal cones to provide an input to accommodation (Fincham, 1951; Kruger *et al.*, 1997b). A second issue relates to the finding that approximately half of the dichromatic observers had no reflex accommodative response to the target (Fincham, 1953). This is an important finding whose clinical significance may have been overlooked.

#### *Monochromatic and reduced bandwidth illumination*

When viewing targets presented in optical systems, many subjects have poorer accommodation responses under reduced spectral bandwidth illumination (Kruger *et al.*, 1993, 1997a; Aggarwala *et al.*, 1995a,b), although some continue to focus normally (Charman and Tucker, 1978; Bobier *et al.*, 1992; Kotulak *et al.*, 1995; Kruger *et al.*, 1997a). Thus, in natural viewing conditions there is the potential for poor accommodation in monochromatic (e.g., low pressure sodium) or reduced bandwidth light (e.g., high pressure sodium). However, there is no consensus on whether accommodation is impaired under these conditions (Jenkins, 1963; Piper, 1981; Corth, 1983; Chisum *et al.*, 1987).

#### *Colour and visual displays*

The colour visual display terminal (VDT) is now widely used in many societies. The cathode ray tube (CRT) is most common, while colour LCDs may be found in portable computers and as flat panel displays. There are three main issues relating to the use of colour in visual displays to ensure comfortable accommodation. The first relates to isoluminance. While three studies have found poor accommodation to isoluminant and near-isoluminant colour targets presented in Badal optical systems (Wolfe and Owens, 1981; Mathews and Kruger, 1990; Switkes *et al.*, 1990), other studies using more natural viewing conditions have found reasonably accurate responses to subjectively brightness matched colour targets positioned at near working distances (Lovasik and Kergoat, 1988; Charman, 1989), even after 4 hr of an intensive search task (Lovasik *et al.*, 1989). Subjects in the latter studies may have been using normal proximal cues to accommodation to compensate for the poor reflex response

to the targets. Even though the evidence is conflicting as to whether isoluminant targets are detrimental to accommodation in natural viewing conditions, it may be better for the designer or computer user to avoid these targets. Text should be of a high luminance contrast for best reflex accommodation (Mathews and Kruger, 1989, 1990; Switkes *et al.*, 1990).

The second issue, which has not been widely addressed, is that it may be better to avoid certain saturated colours because many people have poorer reflex accommodation to monochromatic and reduced spectral bandwidth targets (see previous Section). For example, saturated red text on a black background may have reduced spectral bandwidth due to both the narrow radiance profile of the display's red phosphor (or LCD panel) and due to truncation in the long wavelengths provided by the observer's spectral luminous efficiency function. Studies using natural viewing have either found reasonably accurate responses (Lovasik and Kergoat, 1988; Lovasik *et al.*, 1989) or variability between subjects (Charman and Tucker, 1978) when viewing reduced spectral bandwidth targets. Nevertheless, it may be better to use desaturated colours for critical tasks.

Finally, due to the eye's longitudinal chromatic aberration, certain combinations of saturated colours present conflicting demands to the accommodation system. For example, when viewing saturated red text on a saturated blue background, focusing on the red border requires more accommodation than for the blue border. Both colours cannot be focused simultaneously unless wavelengths from both targets are sufficiently close such that the difference in refractive error between the wavelengths (Thibos *et al.*, 1992) is smaller than the eye's depth of focus (Campbell, 1957). People tend to adopt different and individual focusing strategies when confronted with these conflicting colour combinations (Charman, 1989). To avoid these conflicting stimuli to accommodation, either one or both colours should be made desaturated (Krueger and Mader, 1982).

#### *Transverse chromatic aberration*

Large amounts of transverse chromatic aberration may disrupt the normal stimulus to accommodation provided by longitudinal chromatic aberration due to relative phase shifts between the long, middle and short wavelength components of the retinal image. Transverse chromatic aberration can be significant in common situations such as viewing through single vision or bifocal spectacle lenses (Jalie, 1984), spectacle prism corrections (Smith and Atchison, 1997), optical instruments such as binoculars (Smith and Atchison, 1997), or when viewing colour visual displays in which

there is misconvergence of red, green and blue images. However, one study has found no significant effect of TCA on the static accommodation stimulus-response function to a Snellen letter 'E' target for various levels of induced horizontal TCA up to 6.9 minutes of arc (Bobier *et al.*, 1992).

### Emmetropization

Longitudinal chromatic aberration may also provide a signal for the emmetropization process. This possibility has been considered with regard to human emmetropization (Cobb, 1993), but rearing in monochromatic light does not disrupt the emmetropization process in either chickens (Schaeffel and Howland, 1991; Rohrer *et al.*, 1992; Wildsoet *et al.*, 1993) or Cichlid fish (Kroger and Wagner, 1996). These negative findings would not rule out an influence for longitudinal chromatic aberration if multiple emmetropization mechanisms operate in these species. A more direct test of whether longitudinal chromatic aberration influences emmetropization would be to expose animal eyes to grating simulations similar to those used in the present study, but modified to account for the animal's contrast sensitivity function and photoreceptor characteristics, and for the eye's longitudinal chromatic aberration and modulation transfer function.

### Conclusions

Accommodation responds to static simulations of the effects of defocus and longitudinal chromatic aberration. In association with previous research, it can be concluded that longitudinal chromatic aberration provides an important stimulus to reflex accommodation both when the object of interest is moving and when it is stationary.

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## Appendix

To verify that the longitudinal chromatic aberration of the eye did not significantly alter the chromatic components of the simulations, the most extreme accommodative errors occurring on any occasion during the study were determined. Accommodative errors ranged between a lag of  $-2.7$  D and a lead of

+2.8 D. Modulation transfer functions were calculated using the Chromatic Eye (Thibos *et al.*, 1992) and the physical optical modulation transfer function of Hopkins (1955). The MTF for the green image component had a maximum value of 0.80, falling off to 0.67 and 0.65 for accommodative errors of  $-2.7$  and  $+2.8$  D respectively. The red, green and blue image components did not encounter spurious resolution (Smith, 1982) over this range of focusing errors. For a  $-2.7$  D lag of accommodation, and when compared to the green

image component, the red image component had 7% too little contrast and the blue image component 9.4% too much contrast. For a  $+2.8$  D lead of accommodation, the red component had 2.6% too much contrast and the blue component 8.6% too little contrast. These differences would not have materially altered the chromatic components of the simulations (*Table 1*). Note that the above percentage errors should be multiplied by the values in *Table 1*, rather than added to or subtracted from those values.