Pattern-related visual stress, chromaticity and accommodation

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Word count: 4612

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Abstract

Purpose: To investigate the impact of coloured overlays on the accommodative response of individuals with and without pattern-related visual stress (PRVS), a condition in which individuals manifest symptoms of perceptual distortion and discomfort when viewing a 3 cycles per degree square-wave grating.

Methods: Under double-masked conditions, 11 individuals who reported PRVS selected an overlay with a colour individually chosen to reduce perceptual distortion of text and maximise comfort (PRVS group). Two groups of controls, individually matched for age, gender and refractive error were recruited. Control Group 1 similarly chose an overlay as maximising comfort. Control Group 2 used the same overlays as the paired PRVS participant. The overlay improved reading speed by 10% ($p<0.001$), but only in the PRVS group. Using a remote eccentric photorefractor, accommodative lag was recorded while participants viewed a cross on a background. The background was uniform or contained a black grating and was either grey in colour or had a chromaticity identical to that of the chosen overlay. There were therefore four backgrounds in all.

Results: Overall, the accommodative lag was 0.44D greater in the participants with PRVS. When the background had the chosen chromaticity, the accommodative lag was reduced by an average of 0.16D ($p=0.03$) in the PRVS group, but not in the symptom-free groups: in Control Group 2 the coloured background slightly *increased* the accommodative lag.

Conclusion: Accommodative lag was greater in individuals susceptible to pattern-related visual stress and was reduced by coloured backgrounds.

1. Introduction

The accommodative response is known to vary with many factors including refractive error [1], refractive error stability [2-4], target size [5], target luminance [6], target spatial frequency [7] and method of stimulus presentation.[1,2,4] When viewing a target at a proximal distance, e.g. when reading, an accommodative lag (or under-accommodation relative to the stimulus) of up to 0.50D is expected.[8] The object of regard will remain clear provided the accommodative error lies within the depth of focus of the eye. The depth of focus depends on a variety of factors including pupil diameter, lighting conditions and the target viewed.[9] Inappropriate accommodative responses, such as under-accommodation or over accommodation relative to the plane of the object of regard are a frequent correlate of aesthenopia.[10]

Differences in accommodative response in persons experiencing visual discomfort from near work have been reported. Simmers *et al.* [11] found increased accommodative microfluctuations in a small sample of individuals who found benefit from coloured filters, but the accommodative stimulus response function was normal. Chase *et al.* [12] found a significant positive correlation between symptoms of visual discomfort with near work and accommodative lag (measured objectively using an open-field autorefractor). The prevalence of accommodative insufficiency was much higher than estimated by clinical measures. Tosha *et al.* [13] reported lag of accommodation to increase over a 90s measurement period, with the increase being more pronounced in individuals with high visual discomfort.

Sometimes symptoms of visual discomfort are associated with perceptual distortion, usually of text, in which case they have been referred to as visual stress. Coloured filters have been recognised to alleviate symptoms of visual stress[14-18] although the mechanisms are poorly understood[19]. The coloured filters can take the form of coloured sheets placed upon the page when reading or coloured lenses worn as spectacles. Ciuffreda *et al.* [20] examined the accommodative response in a group of tinted lens wearers.

No significant differences were found in accommodative responses with and without the coloured lenses.[20]

Any form of image degradation (due to contrast, luminance, or spatial frequency composition) will have a negative impact on the effectiveness of a target as a stimulus to accommodation. When the stimulus to accommodation is text or gratings, and the material is subject to perceptual distortion, as is the case in people who experience PRVS [21,22], an associated change in accommodation might be anticipated.

Coloured overlays have been shown to improve reading speed in persons who report perceptual distortions of text and gratings that the overlays reduce. Hollis and Allen [23] showed that the increase in speed could be better predicted from the perceptual distortion reported when gratings are observed than from reports of symptoms in extensive questionnaires of the kind used to measure visual discomfort.[24]

Whereas previous work has used either a Hartinger coincidence-optometer[20] or an open field autorefractor[11-13] requiring instrumentation proximal to the participant, we used an eccentric photorefractor (*PowerRefractor*, Multichannel systems, Germany) from a distance of 1m leaving the proximal field unimpeded. In previous studies, the lack of an internal fixation target or enclosed viewing in the open field autorefractor reduced the risk of proximal accommodation (and thereby an increase in the accommodative response) but did not remove it.[25]

2. Methods

The participants were recruited, by advertisement, from the student population attending Anglia Ruskin University. All participants gave informed consent following a written and verbal explanation of the procedures involved. All procedures conformed to the tenets of the Declaration of Helsinki and were approved by the Anglia Ruskin University Ethics Committee.

Two experiments were undertaken. The first experiment involved the use of individually chosen filters in two groups, one (PRVS) with symptoms of visual stress and one (Control Group 1) with no symptoms. The first group showed improvements in reading speed with the chosen filters, whereas the second did not. In the second experiment, Control Group 2 (yoked controls) similarly matched to the PRVS for age and optometric status used the same filters as those chosen by the symptomatic group. The first experiment was undertaken in Sessions 1 ,2 and 3. The second experiment was undertaken in Sessions 4, 5 and 6.

Experiment 1

Session 1: Screening for PRVS and Control Group 1 participants

Eighty three young adults (51 females and 32 males aged between 18 and 25 years) attended an initial screening session to exclude any participants with migraine and significant optometric and binocular vision anomalies. Symptoms described by persons suffering from PRVS such as headaches, blurring and words moving on the page are non-specific and may also be caused by refractive error or binocular anomalies. The inclusion criteria are shown in Table 1.

Table 1. Inclusion criteria

Visual acuity of at least 6/6 in each eye
Cover test of $< 5\Delta$ horizontal phoria and $< 0.5\Delta$ vertical phoria
No slip evidenced on fixation disparity (Mallett unit)
No diplopia reported during the ocular motility test
Near point of convergence (RAF rule) $\leq$ 10cm
Amplitude of accommodation (push up RAF rule) normal for age (greater than 10D)
Stereo acuity (Titmus circles) of < 80 seconds of arc
Normal red/green colour vision (Ishihara)
Astigmatism of < 0.75DC

In addition to the above tests all persons attending the initial session had an objective assessment of their refractive error using a Nidek AR-600A autorefractor [26] and their susceptibility to PRVS was assessed using the pattern glare test as follows. The desk surface was illuminated by the light from a compact fluorescent lamp with a correlated colour temperature of 3500K. At a distance of 0.4m, participants were shown a grating with square-wave luminance profile, Michelson contrast about 0.9, spatial frequency 3 cycles per degree, circular in outline, radius 13 degrees. They were asked a series of questions regarding the perceptual distortions that they experienced, each beginning "Looking into the centre of the grid that is in front of you….. Do you see any of the following? Please answer each question with either yes/no. Pain/discomfort; shadowy shapes amongst the lines; shimmering of the lines; flickering; red; green; blue; yellow; blur; bending of the lines; nausea/dizziness; unease." Wilkins [21] has used this technique to identify whether people are likely to have susceptibility to PRVS. Individuals with scores of 4 or more indicate that a person may have a sensitivity to pattern glare and experience symptoms. [23]

There were 4 males and 7 females (aged 18-25) with pattern glare scores greater than 3 who were selected to continue to Sessions 2 and 3. Eleven controls having pattern glare scores less than 3, were also selected, matched for age, gender and refractive error. (Individuals with scores of 3 were omitted). The controls were matched for mean spherical equivalent refractive error (spherical power + half cylindrical power) to individuals in the PRVS group because ametropia has been shown to influence the accommodative response. [1-4]

<u>Session 2: Overlay assessment and administration of the Rate of Reading Test for PRVS Group and Control Group 1</u>

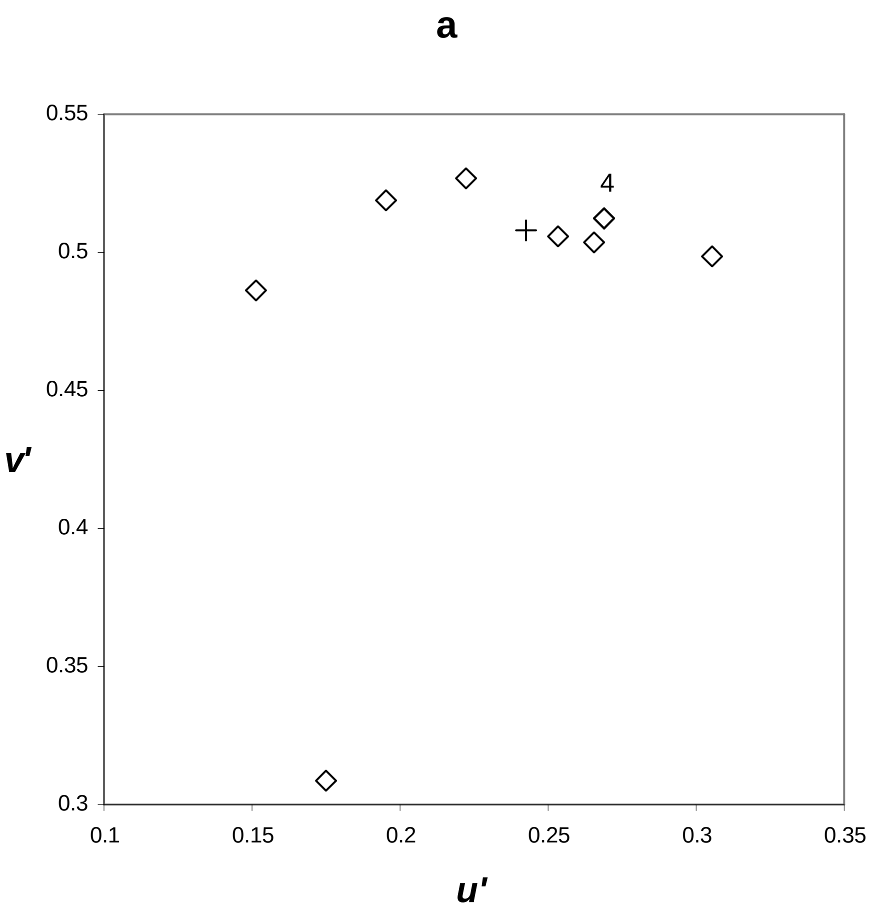
During Session 2 and without knowledge of the above classification, the first experimenter undertook additional measurements of reading speed with and without overlays. All subjects with habitual refractive correction were corrected using spherical contact lenses to within 0.25D. The Intuitive Overlay system (ioo Sales Ltd, London) was used. Following the procedure recommended in the manual, all 22 participants chose from the

Intuitive Overlays the colour of overlay that best improved the clarity and comfort of the text it covered. The Rate of Reading test[27] was administered four times, first with then without, then again without and finally with an overlay. The ABBA design was to minimise practice effects. Most of the practice effect occurs from the first to the second administration and the ABBA design therefore biases any mean difference against a benefit. An average rate of reading with and without the overlay was calculated, along with the percentage difference between the two conditions and the scores are shown later in Table 2.

Session 3: Measurements of accommodation of PRVS group and Control Group 1

A third experimenter conducted the investigations in Session 3 without knowledge of the findings obtained in Sessions 1 and 2 or the allocation of participants. A slideshow program was constructed to display three targets on the LCD screen of a laptop computer mounted orthogonal to the line of sight at a distance of 0.5m from the eyes, the minimum at which it proved possible to obtain an adequate image of the pupil used by the photorefractor. The targets were: (1) a grey field with a central fixation cross having horizontal and vertical lines each 3mm long; (2) the same cross superimposed on a horizontal grating with square-wave luminance profile, Michelson contrast about 0.9, spatial frequency 1.3 cycles per degree, circular in outline, radius 13 degrees; (3) a passage of text consisting of randomly ordered common words. The sequence of presentation used an ABBA block nested within an ABBA block to reduce practice effects.

To ensure that the chromaticity of the background on the screen matched that of the coloured overlays, the coloured overlays selected by the subjects were placed on white paper illuminated as during the screening test. They were observed through one of two circular apertures in an opaque surface in an otherwise dark room. The 302mm x 228mm liquid crystal (LCD) was viewed through the other aperture and the hue and saturation of the display adjusted to match the colour appearance of the two apertures. The various chromaticities of the screen background (measured with a Minolta TV color analyser II) are shown in Figure 1.



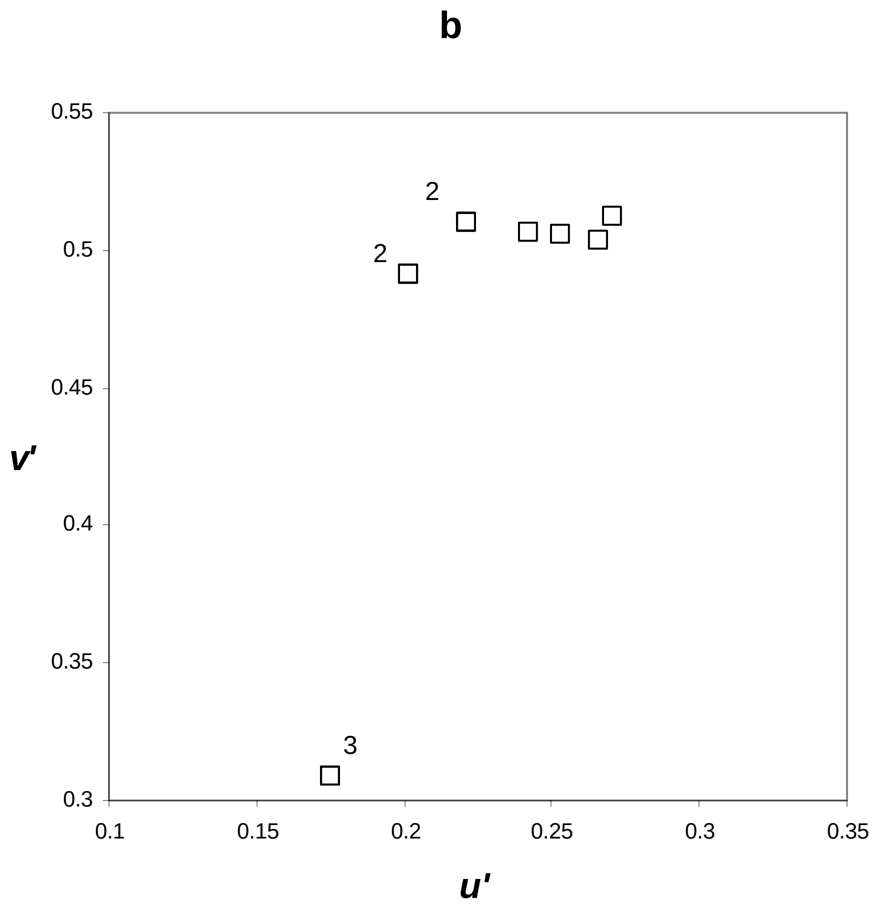


Figure 1. Chromaticities of the screen background. a: PRVS group and Control Group 2 (identical); b: Control Group 1. The cross in 1a shows the chromaticity of the grey screen. Beside each point is indicated the number of participants who chose the colour, if more than one.

INSERT FIGURE 1 ABOUT HERE

The accommodative response was measured using a *PowerRefractor* (Multi-Channel Systems, Germany) at a distance of 1m while each of the targets in the presentation was observed on the laptop screen. The *PowerRefractor* is an eccentric photo-refractor that captures reflected infra red light from the participant’s eye. The *PowerRefractor* was used in the monocular mode whereby the refractive error was measured dynamically in the vertical meridian of the eye at a frequency of 25 Hz, so that a reading of refractive error and pupil size was taken once every 0.04 seconds, for ten seconds. Allen, Radhakrishnan and O’Leary [26] showed the validity and repeatability of the *PowerRefractor* is high, with no significant difference being found between measurements obtained with the *PowerRefractor* and subjective refraction. The 95% limits of agreement in monocular mode ranged from -0.32 to +0.62D.

The use of an adjustable chin and forehead rest allowed optimum positioning of the right eye in line with the centre of the *PowerRefractor* head, thereby reducing artefacts and parallax error due to head movement. All subjects with habitual refractive correction were corrected using spherical contact lenses to within 0.25D. In order to ensure all participants were optimally corrected any small residual refractive errors were corrected where necessary using trial lenses, the maximum additional trial lens used being 0.25D. This was necessary in only 3 participants (one from the PRVS group and 2 from Control Group 1).

Due to large variations in calibrations among participants, [28,29] the *PowerRefractor* was calibrated for each participant individually. For calibration, the left eye fixated a 6/9 letter placed at 6m. The right eye was occluded with an infrared transmitting Wratten 87c filter. Trial lenses (+4.00 to -1.00DS) were placed in front of the Wratten filter which was occluding visible light from the right eye. Measured refraction was compared to the refraction expected from the trial lenses, with allowances made for a vertex distance of 12mm. The correction factor was taken from the slope and intercept of the linear regression trendline, and used to calibrate the *PowerRefractor* measurements from that participant. Before starting calibration of the *PowerRefractor*, the participants dark adapted for 4-5 minutes to allow dissipation of any transient changes in the tonic position of accommodation due to previous near work.[30] Following calibration, all viewing was binocular, although measurements were taken from the right eye.

The convergence required to fixate the cross was approximately 7 degrees. This is within the tolerance of the *PowerRefractor* (approximately 0.50D change in apparent accommodation with gaze 25 degrees eccentric to the optical axes).[31]

The order of slide presentation was the same for all of the participants. The participants initially viewed a cross (A) and then a grating (B) on a grey background for 10s in an ABBA design. Then they were asked to read a passage of text for 45s with a grey (A) and coloured (B) background in an ABBA design. The colour was similar to that individually chosen during Session 2 (Overlay assessment and administration of the Rate of Reading Test for PRVS Group and Control Group 1). Next the participants were required to look at a cross (A) and grating pattern (B) with their chosen coloured background again in an ABBA design and finally the first 4 presentations (cross and grating on a grey background) were repeated. Participants were asked to concentrate on the central fixation point (a cross superimposed on the uniform background or on the grating, luminance $76cd.m^{-2}$) for a duration of 10s. With the prose targets the subjects were asked to read the displayed text for durations of 45 seconds. Brief rest periods were taken after each measurement.

Experiment 2

The purpose of Experiment 2 was to provide 'yoked' controls who used background colours identical with those used by the PRVS group in Experiment 1.

As in Experiment 1, the participants (Control Group 2) were recruited from the student population attending Anglia Ruskin University, 4 males and 7 females, aged 18-24. As before, the participants had pattern glare scores less than 3 and were chosen so as to match the PRVS group with regard to gender and age. The same inclusion criteria were adopted (Table 1).

Experiment 2 was conducted in three sessions (Sessions 4, 5 and 6, corresponding respectively to Sessions 1, 2, and 3 in Experiment 1). The sessions were identical to those in Experiment 1 apart from the exclusion of the conditions in Session 3 (measurements of accommodation) in which the participants were required to read.

Masking

The participants and the experimenters who undertook the reading rate measurements were unaware of the group allocations; the participants were first and second year students unaware as to the purpose of the pattern glare test.

Data integrity

Because of eye movement, the data obtained during reading in Experiment 1 Session 3 (measurement of accommodation) were technically poor, and were rejected. The remaining recordings allowed the comparison of two target types (Cross and Grating) on two backgrounds (Grey and Coloured) for each of the three groups (PRVS group and the two control groups).

3. Results

Table 2 summarises the clinical data and the results of the screening used to group the participants, and also includes the rate of reading.

Table 2. Mean scores (SD and *range*, where appropriate) for the characteristics used to group the participants (pattern glare score) and the reading rates with and without an overlay.

	Mean Pattern Glare Score	Mean Age (years)	Mean Spherical Equivalent Refractive Error (D)	Mean reading rate without overlay	Mean reading rate with overlay	Percent difference in rate
PRVS Group	4.91 (0.94) *(4–7)*	20.6 *(18-25)*	-1.28 (2.29) *(+0.63 – -7.02)*	152 (32.7)	167 (37.9)	9.9%*

Control Group 1	1.00 (0.82) *(0–2)*	20.6 *(18-24)*	-1.47 (1.49) *(+0.50 – -4.26)*	171 (18.3)	172 (19.8)	0.5%
Control Group 2	0.82 (0.75) *(0–2)*	20.8 *(18-24)*	-1.22 (2.05) *(+0.75 – -6.75)*	166 (13.4)	165 (10.3)	-0.1%

* p<0.001, t-test

The mean results in each condition of Experiment 1 are presented in Figure 2. The accommodative response data presented here is the average response over the 10s measurement period. Any periods of data loss e.g. when a participant blinked have been removed, together with the associated artefact.[26] From the figure it can clearly be seen that the lag of accommodation was greater for the group with PRVS than for Control Group 1. As can also be seen, the effect of colour was to reduce the lag of accommodation for the PRVS group and marginally to increase it for Control Group 1. These effects were confirmed in an analysis of variance with colour and stimulus as within-subject factors and participant group as a between-subject factor. The analysis revealed a significant effect of group, $F(1,20)=9.04$, $p=0.007$, $\eta^2= 0.017$, but not of colour, and a significant colour by group interaction term, $F(1,20)=6.86$, $p=0.016$, $\eta^2=0.117$.

Separate analyses of variance for the two groups of participants revealed a significant main effect of colour for the PRVS group: $F(1,10)=5.86$, $p=0.036$, $\eta^2=0.136$, and no significant main effect for Control Group 1. There were no other significant effects or interactions apart from an effect of stimulus, present in all analyses. For example, the overall analysis of variance revealed a significant effect of stimulus such that for both groups of participants the accommodation was weaker with the cross as stimulus than with the grating, $F(1,20)=6.02$, $p=0.02$, $\eta^2=0.077$.

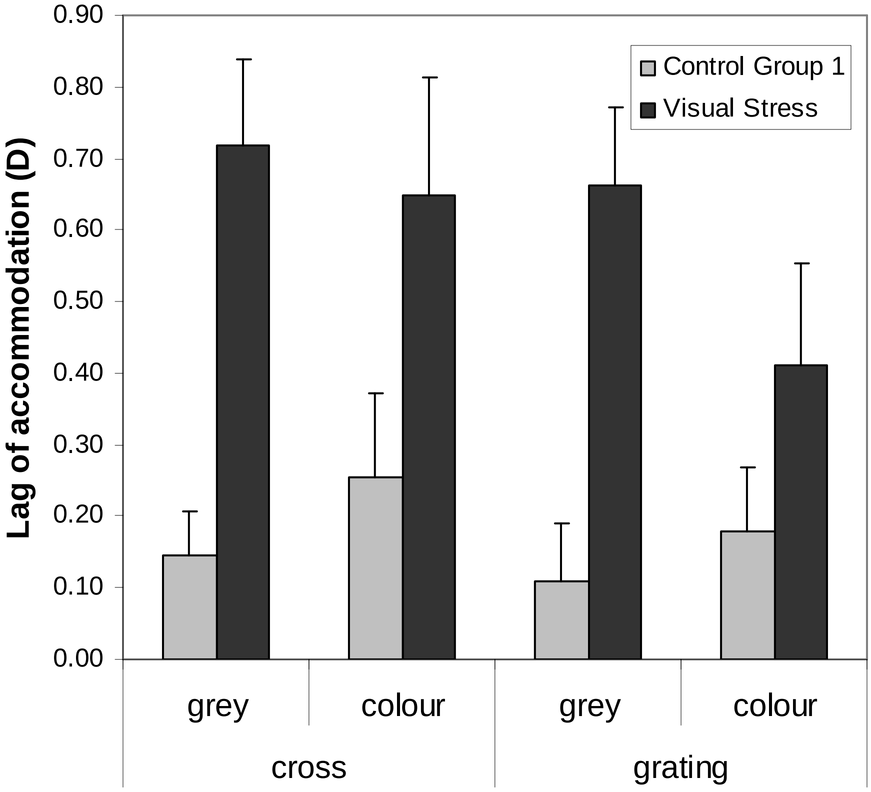


Figure 2. Mean lag of accommodation when viewing cross and grating targets on grey or coloured backgrounds for participants with and without visual stress. Error bars indicate standard deviation.

INSERT FIGURE 2 ABOUT HERE

In order to assess accommodative microfluctuations, we calculated root mean square deviation of the accommodative response, following Anderson *et al*.[32] :

$$\text{RMSdeviation} = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(x_i - \bar{x})^2}$$

We found no significant correlation between rms value and the mean accommodative response, so we analysed the variation separately. The rms deviation was significantly greater in Control Group 1 than the PRVS Group irrespective of the colour of the background (0.592 vs 0.359 dioptres, $p=0.01$). The difference remained when the signal was detrended and bandpass filtered in the frequency range 0.2-0.6Hz (p=0.03), a range suggested by the work of Simmers *et al.* [11]

The chromaticities of the coloured screen shown in Figure 1 were used to calculate the hue angles of the screen relative to the grey. The hue angle was used to obtain the dominant wavelength of the stimulus: the monochromatic light that, when additively mixed in suitable proportions with the reference white light matches the colour of the stimulus. The Spearman rank correlation across participants between the dominant wavelength and (1) refractive error and (2) mean accommodative error when viewing the coloured screen were -0.25 and -0.27 respectively, both non-significant.

The photorefractor measurements included concurrent measurements of pupil diameter. On average the pupil diameter of the PRVS group (4.8mm, minimum 3.8mm) was slightly greater than for Control Group 1 (4.4mm, minimum 3.5mm), although analysis of variance failed to reveal any significant main effects or interactions.

The association between the refractive error measurement by autorefractor in Sessions 1 and 4 (initial screening) and the average lag of accommodation measured by photorefractor when the uniform grey background was viewed is shown in Figure 3. The correlations were PRVS group: r = 0.49, p = 0.06; Control Group 1: r = 0.65, p = 0.01; Control Group 2: r = 0.24, p =0.23.

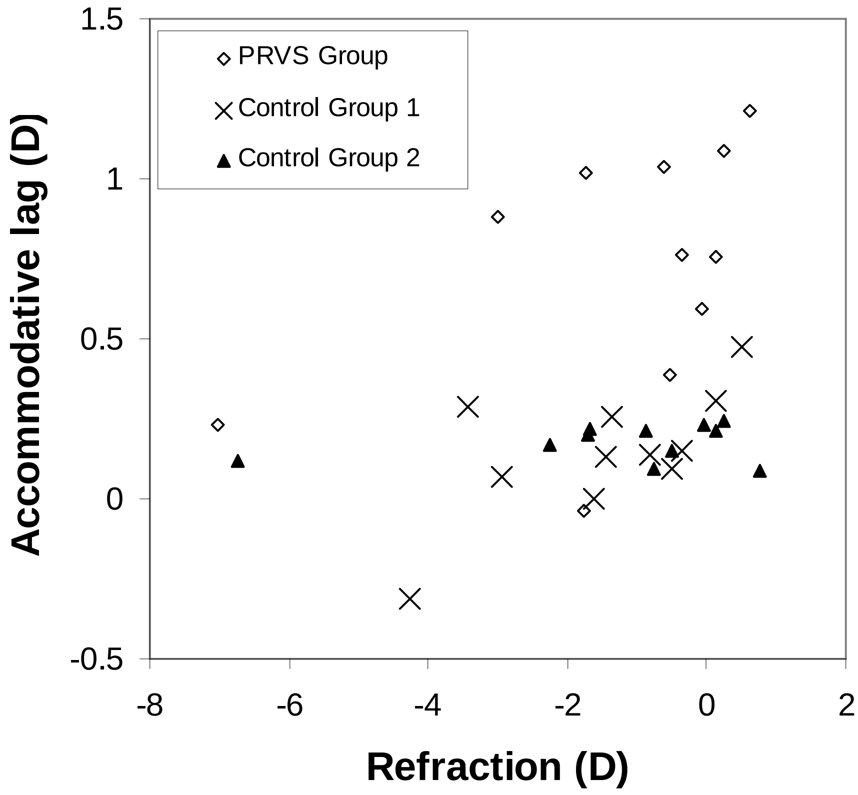


Figure 3. Lag of accommodation as a function of refractive error.

INSERT FIGURE 3 ABOUT HERE

The results of Experiment 2 in which the yoked control group (Control Group 2) participated are presented in Figure 4 and showed a *larger* lag of accommodation on a coloured background than on grey. A repeated measures analysis of variance with colour and target as main effects revealed a main effect of colour ($F(1,10)=6.10$, $p=0.033$, $\eta^2=0.149$) and no other significant effects.

INSERT FIGURE 4 ABOUT HERE

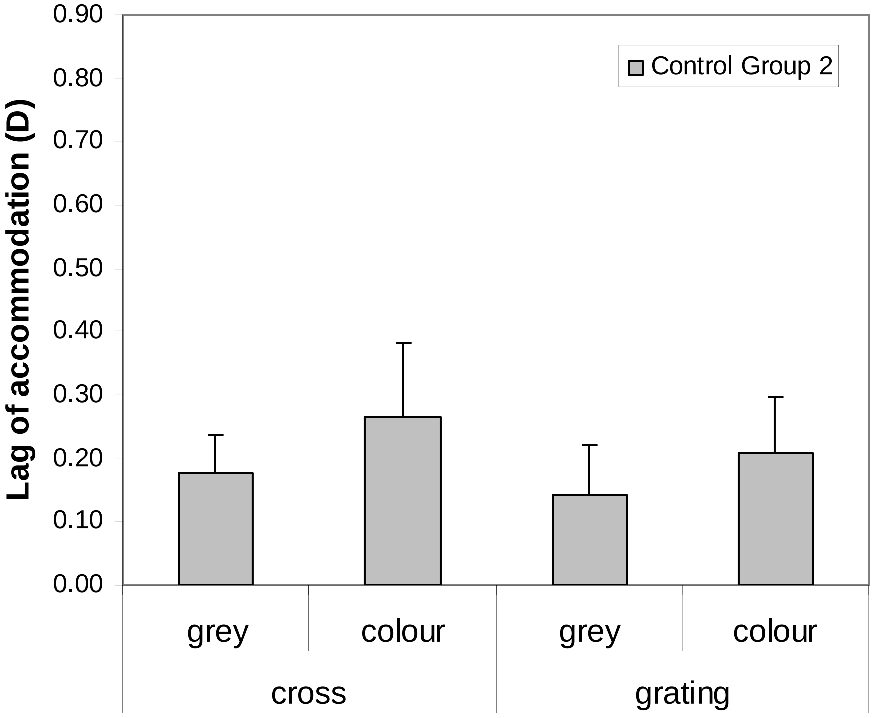


Figure 4. Mean lag of accommodation when viewing cross and grating targets on grey or coloured backgrounds for participants in Control Group 2 – yoked controls. Error bars indicate standard deviation.

The repetition of the grey background at the beginning and end of Sessions 3 and 6 (measurement of accommodation) permitted an assessment of the effects of any fatigue. In the event, there was no statistically significant difference between the first and second presentations for any of the groups ($p>0.05$).

4. Discussion

The accommodative lag was clearly greater for the PRVS group, and, for this group, the coloured background reduced the accommodative lag, although it did not reach the same level as either control group. However, it is striking that in Control Group 2 there was a significant effect of colour, and it was in the opposite direction from that observed in the PRVS group. Indeed in both control groups, the lag of accommodation was *larger* with the coloured background. The reversal in the direction of the effect of colour for the PRVS and control groups cannot be attributed to ceiling and floor effects e.g. to the lower overall lag of accommodation seen in the control groups.

There was an effect of target stimulus, similar for both Control Group 1 and PRVS groups (but not seen in Control Group 2): the accommodation response was slightly greater for the grating than for the cross. The difference was only 0.1D and not therefore clinically significant: both stimuli elicited an adequate accommodative response.

Previous studies used either a Hartinger coincidence optometer [20] or an open-field autorefractor.[11-13] Although the open field autorefractor allowed targets in real space to be used, it necessitated objects in the field of view close to the eyes and nearer than the target. Proximal accommodation may therefore still have been evoked.[25,33,34] Chase *et al.* [12] using a Grand Seiko WAM-5500 autorefractor showed a greater lag of accommodation in individuals with high visual discomfort scores, but only after prolonged recording. There was no difference in accommodative lag between individuals with PRVS and controls in the study by Simmers *et al.*[11] but the sample size was small and the measurement duration was short. However, it is possible to discern in their data a small difference in the same direction as that obtained here. Ciuffreda *et al.* found no difference in accommodative response with and without coloured lenses.[20] The present study differed from previous studies in that the refractive power was measured remotely using an instrument at a distance of 1m with no proximal stimuli.

Measurements of accommodative response have been shown to be influenced by the spatial frequency of the target in both static [7,35] and dynamic measurements.[36,37] Simmers *et al.*[11] used a Maltese cross as a target, and Chase *et al.* [12] a five pointed star, both of which would have provided energy at low spatial frequencies. The present study compared two stimuli – a small cross and a grating, and showed a slightly greater accommodative lag for the former. The cross was evidently a sufficient stimulus for accommodation, given that the accommodative response was within normal limits, but may nevertheless have provided a slightly weaker stimulus to accommodation compared with the gratings. The gratings provided contrast energy in one meridian only, but this was the meridian in which the *PowerRefractor* measured accommodation.

Pupil diameters less than 2.0mm have been found to increase depth of focus, but in the present study pupil diameters were in a range (3.5-6.6mm) that produces fairly stable blur sensitivity.[38] The lack of a significant difference in pupil size between groups and the marginally larger pupil size in the PRVS group combine to indicate that the accommodative findings are independent of pupil size.

The colour of the background was not related to the size of the accommodative lag or to the refractive error. It did not appear that the colour of the background acted to reduce the effects of chromatic aberration because there was no association between the dominant wavelength and the magnitude of the refractive error or accommodative lag.

There are a number of potential mechanisms by which colour may have improved the accommodative response (reduced the lag of accommodation) in the PRVS group. Firstly, Chase *et al.*[39] measured the subjective speed matches between L-, M-, and S-cone isolating stimuli in good and poor readers and suggested that differences in L/M cone ratios in the retina may contribute to reading difficulties. As the L/M ratio influences accommodation[40] then changing the L/M excitation with colour will change the accommodative response. Secondly, if the text is found to be uncomfortable to the reader (PRVS group) because of cortical over activation[21] then blur would reduce such activation due to contrast reduction. If colour reduces overactivation then a reduced lag of accommodation may result.

Irrespective of the colour of the background, the variability in accommodation (accommodative microfluctuation) was greater for Control Group 1 than the PRVS group, which showed the greater accommodative response. This is unsurprising as Day *et al.*[41] have shown that a greater accommodative response results in a larger variability in the response. The present rms values are high, but within the range shown by Anderson *et al.*[32] which was 0.1 - 0.7D for a 2D response amplitude, even in older participants.

These findings with respect to accommodative microfluctuations add to the inconsistencies in the literature. Tosha *et al.*[13] used monocular viewing and showed a larger variability in accommodation at close viewing distances, but no differences between groups with high and low visual discomfort scores. Simmers *et al.*[11] showed a greater variability of accommodation in a small group with PRVS and a reduction in the variability with coloured filters.

Plainis *et al.*[42] suggested that lag of accommodation may be influenced by the change in spherical aberration that occurs during accommodation. Indeed, it has recently been shown that inducing negative spherical aberration in myopes can increase the accommodative response and reduce any lag of accommodation present.[43] Several studies[44-49] have examined the changes in both spherical aberration and other higher-order aberrations during accommodation with variable results, but in general have indicated that with increasing accommodative effort, spherical aberration tends to change from an initially slightly positive value towards a negative value. The various relationships between image quality, higher order aberrations and accommodation are still unsettled and it remains possible that manipulation of aberrations affects accommodation and thereby PRVS.

The spatial frequency of the target viewed during accommodation measurements was 1.3 cycles.deg^{-1} and lower than that at which the pattern glare was measured in Sessions 2 and 5. The spatial frequency of the target grating was low relative to that optimal for the induction of illusions. The spatial frequency of the target grating was a compromise between the requirements to provoke illusions and those necessary to avoid extreme discomfort. We wished to reduce the blinks and gaze aversion associated with extreme discomfort because they would have interfered with the recording. Using a 1.3 cycles.deg^{-1} grating rather than the more aversive 3 cycles.deg^{-1} grating leaves open the possibility that accommodation might have been even more adversely affected in PRVS subjects had a 3 cycles.deg^{-1} target been used.

A major strength of the current study is that it was double-masked. The instructions to participants are known to influence the accommodative response[50] but could not have affected the findings because both the experimenters and participants were unaware of the allocation of groups, or the relevance of the measurements undertaken.

In all studies cited above the participants viewed the stimuli monocularly with the non-viewing eye occluded with a patch. Another strength of the current study is that the participants viewed the stimuli under normal binocular reading conditions. Seidel *et al.*[51] showed that binocular viewing resulted in accommodative responses that were more accurate (showed less lag of accommodation) than those obtained under monocular viewing.

Chase *et al.* [12], who used the Conlon Visual Discomfort questionnaire, found accommodative lag was strongly correlated with symptoms of headache, blur and diplopia, but not with distortions of text. The participants in the present study were selected on the basis of pattern glare scores, which have been shown to better predict the improvement in reading speed with coloured filters [23] than symptom questionnaires. [24]

The differences in accommodative lag observed in the present study were within the range for which associated blur is tolerated. Within this range central mechanisms that are independent of optical factors may predominate. The chromaticity of illumination individually chosen to reduce perceptual distortion has been shown to improve reading speed. If the chromaticity of illumination differs from the optimal chromaticity by a separation of about 0.07 in the CIE UCS diagram the colour offers no improvement.[52] It will be interesting in future work to determine whether the accommodative changes found in this study have similar chromatic specificity, and, if so, whether the reduction in accommodative lag is long lasting.

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Appendix

		MSE	Pattern Glare Score	Chosen Colour	Mean Lag of accommodation
PRVS	1	-0.06	5	Rose	0.68
	2	-1.75	5	Lime	-0.05
	3	-1.73	5	Orange	0.87
	4	-0.52	5	Mint & Mint	0.24
	5	-7.02	4	Pink	0.18
	6	0.63	4	Orange	1.17
	7	-0.37	5	Rose & Orange	0.82
	8	-3	4	Orange	0.62
	9	0.12	6	Aqua & Mint	0.57
	10	0.25	7	Orange	1.02
	11	-0.61	4	Blue	1.05
Control Group 1	1	-3.43	1	Blue	0.23
	2	-1.44	2	Pink	0.21
	3	-4.26	2	Rose	-0.34
	4	-1.63	1	Mint	-0.02
	5	-0.82	0	Mint	0.07
	6	-2.95	1	Aqua	0.16
	7	0.5	0	Orange	0.51
	8	-0.5	0	None chosen	0.01
	9	-1.36	2	Aqua	0.43
	10	-0.37	1	Blue	0.18
	11	0.12	1	Blue	0.34
Control Group 2 (Yoked control)	1	-0.04	1	Rose	0.24
	2	-1.67	0	Lime	0.22
	3	-1.72	1	Orange	0.17
	4	-0.87	2	Mint & Mint	0.10
	5	-6.75	1	Pink	0.34
	6	0.75	0	Orange	0.30
	7	-0.75	1	Rose & Orange	0.14
	8	-2.25	1	Orange	0.11
	9	0.12	0	Aqua & Mint	0.17
	10	0.25	0	Orange	0.27
	11	-0.5	2	Blue	0.12

The appendix shows the mean spherical equivalent refractive error, pattern glare score, overlay colour chosen and mean lag of accommodation for all participants.