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Effect Of Optical Aberrations On The Color Appearance Of Small Defocused Lights

Preeti Gupta, Huanqing Guo, David A. Atchison, Andrew J. Zele

School of Optometry and Institute of Health & Biomedical Innovation, Queensland University of Technology, Kelvin Grove 4059 Q, Australia

We investigated influences of optics and surround area on color appearance of defocused, small narrow band photopic lights (1’ arc diameter, λ_{max} 510 - 628 nm) centered within a black annulus and surrounded by a white field. Participants included seven normal trichromats with L- or M-cone biased ratios. We controlled chromatic aberration with elements of a Powell achromatizing lens and corrected higher-order aberrations with an adaptive-optics system. Longitudinal chromatic aberrations, but not monochromatic aberrations, are involved in changing appearance of small lights with defocus. Surround field structure is important because color changes were not observed when lights were presented on a uniform white surround.

OCIS codes: 330.1750, 330. 4460

1. Introduction

The appearance of a light depends on the context within which the light is presented.[1-6]. Color appearance varies with stimulus area[2-5], position in the field[6] and duration.[7]. The presence of a surround field can also modify color appearance.[8, 9] Imperfections in the eyes optics means that spread light from a surround alters photon absorption in photoreceptors in nearby areas in a spatial frequency[10] and wavelength dependent manner.[11] Longitudinal chromatic aberration causes wavelength-specific defocus of spatially structured chromatic stimuli [12].

Laboratory and field investigations in the railway environment showed that with small amounts of positive defocus (approximately +0.6±0.1 D), small red lights (≤ 1’ arc) change color, typically to a yellowish or white appearance.[13] The change in color appearance cannot be explained by the Abney effect[14-16] or the Bezold-Brücke effect.[17] Wood et al. [13] did not systematically evaluate the effect of chromatic aberrations as the color shift seemed to be in the wrong direction because positive defocus improves the focus of red relative to that of yellow. In this study we consider the effect of longitudinal chromatic aberrations and monochromatic aberrations on the appearance of small, narrow band lights.

Longitudinal chromatic aberrations (LCA) produce wavelength dependent changes in defocus[18] that provide cues for accommodation and depth of focus,[19] but also cause spatial blur[20] and can introduce luminance artifacts for nominally isoluminant stimuli.[21] This high spatial frequency, wavelength dependent luminance signal can be transmitted by neurons in the parvocellullar pathway.[22] The small spectral separation between L- and M-cones minimizes the effect of LCA on the image contrast of high spatial frequency signals,[23] and macular pigment and monochromatic aberrations provide an additional degree of compensation for

LCA.[24, 25] The appearance of stimuli localized to the area of the photoreceptor outer segment[26] is also dependent on the participant's L/M cone ratio, whereas unique yellow settings with 2° fields is not.[27, 28]

In this study, we show that chromatic aberrations, but not monochromatic aberrations, can influence the color appearance of small (1' arc), long and short wavelength narrow band lights. We show that the structure of the surround field is important, but that L/M cone ratios in the normal trichromatic observers are not important.

2. Methods

A. Participants

Seven participants with normal color vision and visual acuity (6/6 or better) were recruited (age range 25-54 years, mean ± SD 32.1 ± 10.3 years). Participants were academic staff and graduate students at the Queensland University of Technology. Approval for the study was obtained from the University Human Research Ethics Committee, and written informed consent was obtained from all the participants after an explanation of the purpose and possible consequences of the study. Two participants were extensively tested in all experimental conditions to determine the underlying trends in the data. The major observations were verified on a larger sample ($n = 7$ in Experiment 1, $n = 6$ in Experiment 2).

Each participant underwent a brief optometric examination, including color vision screening with the Ishihara pseudoisochromatic plates. Each participant had normal color vision according to this test. None of the three female participants were aware of relatives with color vision deficiencies. Experimental testing was conducted monocularly with the non tested eye occluded with a patch. To eliminate accommodation, the participant's right eye was cyclopleged using 1% cyclopentolate and this was applied every 90 minutes with reinstillation as required. Pupils were dilated to at least 6 mm; for three participants, this required an additional drop of 2.5% phenylephrine. Twenty minutes after instillation of the first drop, amplitude of accommodation was assessed by the push-up method (Hartinger hand optometer, Rodenstock). In all cases subjective amplitude of accommodation was less than 2.0 D, and we considered that accommodation had been eliminated.

B. Heterochromatic modulation photometry (HMP) and participant L/M cone ratios

Participant L/M cone ratios were estimated using Heterochromatic Modulation Photometry (HMP).[29] Stimuli were generated using a two-channel, four-primary Maxwellian view photostimulator.[30] In its 4-primary mode, the photostimulator provides independent control of the stimulation of the rods and three cone classes.[31, 32] Only two primaries from each channel were required for the HMP measurements. A pair of heterochromatic lights (558 and 660 nm) were presented in a foveated 2° field (20 Td time average) set within a dim (2 Td) yellow surround (13.5° diameter). The modulation depth of the 558 nm and 660 nm primaries were presented in a series of fixed standard and test luminance ratios (the Red/Green ratio), varied at an alternation rate of 15 Hz.[29] For each primary ratio, the modulation depth was adjusted to determine the threshold value at which the flicker percept disappeared. For estimation of the cone ratio, the luminosity function V(λ) was modeled as a linear sum of the Smith and

Pokorny[33] L- and M-cone fundamentals in a ratio of 2:1. Red/Green ratios were determined from the HMP data and the participants' energy ratio was calculated relative to the standard observer's energy ratio at the primary wavelengths. The results of the analysis indicated that the L/M cone ratio for the seven participants ranged from 2.8 to 0.5. The individual participant L/M ratios, gender (M/F) and ages (years) are as follows: 2.79 F 27; 2.63 M 53; 2.51 F 29; 1.77 M 32; 1.66 M 32; 0.50 F 25; 0.48 M 28. The variation in L/M cone estimates derived from photometric matches has been attributed to a number of sources[27, 34-36]. If individual participants L-cone λ_{max} varied because of serinine / alanine substitutions, this would slightly increase the range of L/M cone estimates (range = 0.45 to 2.84). With less than 19% of the variance in flicker photometric spectral sensitivity due to receptoral and pre-receptoral factors,[36] the range of cone ratios in our sample is wide enough that we can conclude that there are five participants with a preponderance of L-cones and two participants with a preponderance of M-cones.

C. Optical system

Fig. 1A shows a schematic representation of the stimulus. Light from a 12 V, 50 W tungsten halogen bulb was attenuated by diffusers and Kodak Wratten filter No. 29 to produce a narrow band (FWHM 50 nm) stimulus of dominant wavelength 628 nm (1931 CIE x=0.68, y=0.31, Y=6,250 cd/m^2) (Fig. 1B). Other narrow band interference filters were interposed at the same position when required. A black circular disc with a 1 mm aperture was mounted in front of the light, to produce a spot that subtended 1.0 min of arc at 3.4 metres. A white surround included a 4.5 mm aperture (subtending 4.6 min of arc), through which both the 1 mm spot and black surround produced by the circular disc could be viewed. The black annulus was chosen according to the practice of using black boards around signals in railway and traffic lighting. An

LCD projector (EPSON Multimedia, EMP – 1815/1810) was placed below the field of view and produced a uniformly illuminated region (7° x 5°) on the white surround (1931 CIE x=0.29, y=0.34, Y=2,170 cd/m^2). No light was projected onto the black surround and its internal aperture so that the projected light did not illuminate the red light source. The black text 'Focus on this' was projected on the white surround in 24 point Arial font and was 51' above the centre of red spot.

Fig. 2 shows the optical system through which participants viewed the stimulus. The aperture A_1 was 3.4 m from the stimulus, and imaged onto the eye pupil at unit magnification through a series of achromatic doublet lenses and mirrors. A_1 was at the focal plane of 100 mm focal length lens L_1, the eye was at the focal plane of 100 mm fl lens L_4, and L_2 and L_3 made a pair of 200 mm fl relay lenses. M_3, M_4, M_5 and M_6 were reflecting right angle prisms forming an optical trombone, as attributed to Walther Thorner;[37] pair M_4 and M_5 was placed on a movable translator with 1 mm movement equivalent to 0.2 D change in focus. Infrared LEDs illuminated the eye and reflected radiation from the anterior eye passed through the hot mirror H to display the eye image on a monitor via the pupil video-camera. AC was a lens to manipulate chromatic aberration. Trial lenses placed at TF incorporated participants' spherical corrections (3 participants) or cylindrical corrections (2 participants) and extended the focus range of the optical system.

The equivalent luminance of the stimulus and white surround at the eye were 1470 cd/m^2 and 350 cd/m^2, respectively (4.87 log Td and 4.35 log Td for an 8 mm pupil).

D. Controlling longitudinal chromatic aberration (LCA) with the Powell achromatizing lens and its components

The longitudinal chromatic aberration of eyes were corrected by a nominally zero power Powell air-spaced triplet-doublet system lens with longitudinal chromatic aberration equal and opposite to that of the eye.[38] The doublet component of the lens is designed to have the same longitudinal chromatic aberration as the eye, and the triplet component is designed to have twice the reverse of the chromatic aberration of the eye.

Experimental measurements of chromatic aberration were taken to evaluate the performance of the Powell lens and its components. Six narrow band interference filters were presented in a random order, to minimize the effects of learning and fatigue, in the front of the projector. The black annulus and its aperture (Fig. 1) were replaced by a white disk that matched the background. The stimulus projected on the centre of the field consisted of three black vertical lines subtending a vertical angle of 25’ arc and a horizontal angle of 7’ arc. For each interference filter, the participants’ task was to alter the path length of the system using the optical trombone to bring the three black vertical lines into the best possible focus. Six measurements were recorded and averaged for each of the filters and four lens conditions at 4 mm pupil size: without any lens, achromatizing lens, doublet and triplet lens. Because all participants showed similar results across lens conditions, the data for each lens condition were combined and the individual participant results were shifted vertically to minimize the variance in chromatic aberration of the group data across the wavelength range[39].

Fig. 3 shows longitudinal chromatic aberration of the group of 7 subjects. The mean longitudinal chromatic aberrations between 474 nm and 653 nm were 0.8 D without any lens (filled circles), -0.3 D with the achromatizing lens (direction reversed; filled squares), 1.9 D with the doublet lens (unfilled triangles) and -1.2 D with the triplet lens (direction reversed; filled diamonds). The lines are theoretical fits using the Indiana model eye [40] combined with the lens specifications [38]. This figure shows that the Powell lens can be used to control longitudinal chromatic aberration of the eye.

E. Controlling monochromatic aberrations with an adaptive optics system

To investigate the effect of monochromatic aberrations on the appearance of small lights, participants' monochromatic aberrations were corrected with an adaptive optics system in open-loop mode.[41] The system consists of laser calibration, radiation source, pupil position monitoring, wavefront operations and visual stimulus channels (Fig. 4). The *laser calibration channel* contains a 543 nm He-Ne laser and joins with the radiation source and wavefront operation channels at uncoated pellicle beamsplitter BS1 in front of the eye. The *radiation source channel* contains an infrared superluminescent diode (Hamamatsu Photonics, 830 nm, FWHM 25 nm) whose radiation is reflected into the eye at beamsplitter BS1. The *pupil position monitoring channel* contains a Pixelink Pl-A741 firewire camera and an infrared LED illumination ring. The subject's pupil image is displayed on a computer monitor and used to keep the eye aligned by adjusting the position of the bitebar upon which the subjects' head is mounted.

Light reflected from the retina passes along the *wavefront operations channel*. The eye pupil is imaged onto the surface of the deformable mirror, and onto the Hartmann-Shack sensor array. Magnifications are -2 between the pupil and the deformable mirror and 0.5 between the pupil and the HS sensor. An optical trombone varies defocus independent of the mirror (precision 0.1 mm or 0.0088 D), and was used as such in the experiment.

The deformable mirror is a Mirao52 (ImagineEyes, Paris, France) with 52 actuators over 15 mm diameter under a protected silver coating deformable membrane. A comprehensive description of its performance has been given by Fernández et al.[42]. The Hartmann-Shack sensor is a HASO 32 system consisting of a lenslet array, camera and associated software. The lenslet array has 40×32 microlenses with 0.114 mm pitch and 2.2 mm focal length. Modal reconstruction with 65 Zernike polynomials is used to fit wavefronts from slope measurements.

Aberrations of real eyes and model eyes were checked with the system, and we obtained similar values of spherical aberration coefficient C_4^0 as for a COAS-HD aberrometer (Wavefront Sciences). Incorporating defocus by moving the optical trombone gave expected values.

The *visual stimulus channel* splits from the wavefront operations channel at cold mirror BS2. The channel consisted of stop A and the red light stimulus with its surrounds (Fig. 1). In Experiment 2, the stop was either 2.0 mm or 3.0 mm in diameter and the stimulus was 1.7 m from the stop. These sizes are half those used in Experiment 1 because of the magnification provided by the system.

F. Experimental procedures

All experiments were conducted in a dimly lit laboratory with the room lights turned off. The participant's eye position was adjusted initially using a bitebar and an XYZ translation controller. During the experiments the eye was aligned with the achromatic axis. For this, a target with a red square (60 mm x 60 mm, 1931 CIE $x = 0.52$, $y = 0.33$, $Y = 415$ cd/m^2)

surrounded by a blue square (420 mm x 298 mm, 1931 CIE $x = 0.13$, $y = 0.07$, $Y = 250$ cd/m^2) with vertical and horizontal black lines passing through the squares was projected on to the screen. The red and blue color combination was chosen in order to get the maximum chromatic aberration. The intersection of the vertical and horizontal lines coincided with the red light stimulus. The participant moved the bite bar assembly until the black lines appeared aligned across the boundaries between the two squares.

For Experiment 1, investigating the role of longitudinal chromatic aberration on light appearance, participants were first given a short practice run of the procedure for changing the appearance of the small narrow band lights with defocus. Using a 4 mm aperture at A_1, conjugate to the eye(Fig. 2), and without using the achromatizing lens, the participant looked directly at the writing ("Focus on this") and altered the trombone to bring the writing into the best possible focus. This position was recorded by the experimenter as a scale reading on a micrometer caliper attached to the trombone. Six such readings were recorded and averaged to provide a reference focusing position. During the experiment proper, the participant was required to maintain fixation on the narrow band light and defocus it by moving the optical trombone in the positive direction. The participants reported when they noticed a change in the appearance of the narrow band light. This level of defocus was recorded by the experimenter. A set of ten readings were taken. This was repeated for the negative direction. Following measurements for the 4mm pupil and no achromatizing lens, the procedure was repeated in order with the following combinations: 2 mm pupil and no achromatizing lens, 6 mm pupil and no achromatizing lens, 4 mm pupil and achromatizing lens, 4 mm pupil and doublet component, 4 mm pupil and triplet component. The 2 mm and 6 mm conditions were included to determine whether light appearance might be affected by pupil size. The alignment was checked and corrected if necessary for each lens.

Experiment 2, investigating the role of monochromatic aberrations on light appearance, was conducted with 4 mm and 6 mm pupils without the Powell achromatizing lens or its components. The stimulus was the same for the previous experiment, except that the distance to the limiting aperture was reduced from 3.4 m to 1.7 m because the adaptive optics system had a magnification of 0.5. We could have added defocus by changing the shape of the adaptive optics mirror, but instead moved an optical trombone to make the procedure as close as possible to that in Experiment 1. This experiment was conducted under two conditions: (1) no adaptive optics and (2) with adaptive optics correction of astigmatism and higher-order aberrations.

3. Results

A. Experiment 1 - The role of longitudinal chromatic aberration on the appearance of a small, narrow band long wavelength light

Fig. 5 shows the defocus required to produce a change in the appearance of the long wavelength light (628 nm) for the different lens/pupil size conditions. The data are the average (±SD) of the seven participants. The results for each participant were adjusted so that the in-focus response for 4 mm pupil diameter without a lens was zero. Filled circles represent in-focus, filled squares represent positive defocus and unfilled triangles represent negative defocus. Without a lens, all seven participants reported a change in the color appearance with positive defocus with the 4 mm (0.49 ± 0.21 D) and 6 mm pupils (0.48 ± 0.16 D), and two participants reported a change with the 2 mm pupil. The reported appearances varied however. Four out of seven participants reported the appearance as yellow, and three participants reported the appearance as orange. For the 6 mm pupil (no lens), 5/7 participants reported the appearance as yellow and two participants reported a hue change (i.e. not white) but could not specify the color. When LCA was doubled using the doublet lens (4 mm pupil), the change in color appearance occurred for all the participants with positive defocus (+0.62 ± 0.16 D), and the appearance was reported by all observers to be more vivid than with the no lens condition; 5/7 participants reported the appearance as white and 2 reported it as desaturated. When the LCA of the eye was reversed using the triplet lens (4 mm pupil), the change in color appearance was reported with negative defocus (but not positive defocus) in five out of the seven participants (mean -0.54 ± 0.34 D), and these participants reported the appearance as white. By eliminating LCA with the achromatizing lens (4 mm pupil), the change in color appearance was not reported by any of the participants in either the positive or negative defocus directions.

B. Experiment 2 - Effect of monochromatic aberrations on the appearance of a small, narrow band long wavelength light

In the no adaptive optics condition and with 6 mm pupils, the root-mean square wavefront aberrations for the 6 participants ranged from 0.19 μm to 0.52μm without defocus. With the astigmatism and higher-order aberrations correction with the 6mm pupil, the range of residual root-mean square wavefront aberrations ranged from 0.06 μm to 0.10 μm. The luminance of the surround field was determined by a comparison technique with an auxiliary source because of light losses in the optical system. The equivalent luminance of the surround at the eye as averaged from two participants was 360 cd/m^2 (4.0 log Td; 6mm pupil).

Fig. 6 shows the level of defocus required to produce a change in the appearance of the 1’ arc long wavelength light without and with adaptive optics corrections using 4 mm and 6 mm pupils. Again, the results for each participant were adjusted so that the in-focus response for 4 mm pupil diameter without a lens was zero. Filled circles represent the in-focus condition and filled squares represent the amount of positive defocus required by the participants to observe a change in the appearance of the light. The results for each participant were adjusted so that the in-focus response for 4 mm without or with adaptive optics correction was zero. The change in color appearance was reported by all six participants with both pupil sizes and positive defocus, both with and without aberration correction. There was no significant difference in the level of defocus required with and without correction of monochromatic aberrations (paired t-tests: 4 mm pupil without AO +0.44 ± 0.18 D, 4 mm pupil with AO +0.46 ± 0.16 D, $p = 0.48$; 6 mm pupil without AO +0.42 ± 0.12 D, 6 mm pupil with AO +0.44 ± 0.15 D, $p = 0.67$).

C. Experiment 3 - Effect of longitudinal chromatic aberration on the appearance of small short and long wavelength lights

To determine if the change in appearance of small lights with defocus was wavelength specific, we studied the effect of defocus on the appearance of long and short wavelengths. In the first part of the experiment, the participants performed a qualitative assessment of the change in color appearance with defocus for narrow band wavelength lights between 510 nm and 618 nm. In the second part of the experiment, quantitative results were obtained for a short wavelength light (532 nm filter) under a range of viewing conditions.

Two experienced psychophysical participants from the previous experiments took part (DAA, PG). The same equipment and procedures were used as described for Experiment 1. The light source was attenuated using narrow band interference filters (dominant wavelengths 510 nm, 532 nm, 549 nm, 589 nm and 618 nm, FWHM 10 nm) (Fig. 1). The luminance of the white background was adjusted so that the Weber contrast of each stimulus was approximately 190 %. The experiment was performed using a 4 mm aperture, without any lens and with the achromatizing lens, doublet and triplet lenses.

The results of the first part of the experiment demonstrated that a change in appearance of the small lights occurred with defocus for all the short and long wavelength lights tested, except for 510 nm. The two participants described similar appearances at most combinations of wavelength, lens types and focus. Most wavelengths appeared desaturated for the in-focus condition, and became more so in one direction. The directions for the change in color appearance were reversed for short wavelengths (532 and 550 nm) relative to the effects for long wavelengths (589 nm and 620 nm) as reported for Experiment 1: without a lens, the phenomenon occurred in the positive and negative directions for long wavelengths and short wavelengths, respectively; with the achromatizing lens the phenomenon was not reported; with the doublet the phenomenon occurred in the same directions as without a lens, but was more pronounced; with the triplet the phenomenon occurred in the negative and positive directions for long wavelengths and short wavelengths, respectively.

The quantitative observations of the change in color appearance with defocus with the 532 nm filter (4mm pupils) indicated it was strong and reliable with the different lens conditions. The stimulus already appeared slightly desaturated for the in-focus condition (see Discussion), and so the participants were instructed to determine the minimum defocus that produced the maximum change in appearance, which was the strategy both participants used for the long wavelength light in Experiment 1. Fig. 7 shows the minimum defocus required by the participants to produce maximum desaturation of the 532 nm light for the different lens conditions. Filled circles represent the in-focus setting, filled squares represent positive defocus and unfilled triangles represent negative defocus. As in Experiments 1 and 2, results were adjusted so that the in-focus response for 4 mm pupil diameter without a lens was zero. Both participants showed similar results. Without a lens, maximum desaturation occurred with negative defocus of approximately -0.3 D (DAA -0.32 ± 0.08 D; PG -0.33 ± 0.09 D; standard deviations determined by assuming standard deviations for in-focus and defocused conditions were the same), but desaturation did not occur with positive defocus. With the doublet lens, the phenomenon also occurred with negative defocus, but with slightly higher magnitude (DAA -0.40 ± 0.23 D; PG -0.43 ± 0.44 D). With the triplet lens, maximum desaturation occurred with positive defocus of approximately +0.3 D (DAA + 0.34 ± 0.11 D; PG +0.35 ± 0.10 D) but desaturation did not occur in with negative defocus. As the change in color appearance did not occur with the full achromatizing lens, no observations were made with it.

The magnitude of defocus required to produce the change in appearance were similar at the two wavelengths (532 and 628 nm) for the two participants: no lens means +0.3 D for 628 nm and -0.3 D for 532 nm; doublet means +0.5 D for 628 nm and -0.4 D for 532 nm; triplet DAA -0.3 D for 628 nm and +0.3 D for 532 nm (PG could not appreciate change in appearance at 628 nm).

4. Discussion

Longitudinal chromatic aberration, but not monochromatic aberration, is involved in changing appearance of small lights (1’ arc diameter) with defocus across the visible spectrum, with directions of effects being reversed for short wavelengths relative to those for long wavelengths.

Without a lens to alter longitudinal chromatic aberration, change in color appearance occurred with positive defocus for long wavelengths and negative defocus for short wavelengths. By eliminating LCA with the achromatizing lens, no change in color appearance was reported. When LCA was doubled the color change occurred in the same directions as without a lens, but was reported to be more vivid. By reversing the LCA with a triplet lens, the direction of the defocus required for the color change was reversed and the phenomenon occurred in the negative and positive directions for long wavelengths and short wavelengths, respectively. Shorter wavelengths appeared slightly desaturated for the in-focus condition, and became more so in one direction. The amount of defocus required to produce the change in color appearance was similar at 532 nm and 628 nm. L/M cone ratio did not affect the appearance of the small narrow band stimuli as all participants, despite a large ratio range, described similar changes in color appearance. Hofer et al.[26] demonstrated that color appearance depends on a participant's L/M cone ratio when stimuli are localized to the photoreceptor outer-segment. Our experimental conditions allowed for both continuous viewing and eye-movements, and the point-spread function of the stimulus would cover a larger number of photoreceptors (>9). Further work may determine if there exist viewing conditions in the natural environment for which color appearance depends on cone ratios.

The appearance of a light depends on other lights in view. In this study, the luminance contrast of the surrounding background field played an important role in determining the color appearance of small defocused lights. In a control experiment, the black annulus and white background were exchanged. The white annulus was set to be ~20% of the luminance of the small stimulus for 532 nm and 620 nm filters, and its size was varied. If there was no white annulus or its diameter was 2.5', the color of the small light was seen, but there was no change in the color appearance with defocus in either positive or negative directions for either filter. For larger diameters, the color of the small light could no longer be appreciated either in or out of focus (i.e. the colored light appeared achromatic).

The participants had differences in their in-focus positions for the different lens conditions. The differences may be attributed to the wavelengths at which the different participants were focusing. In Experiment 1, changes in the in-focus position relative to that for the no lens condition were as follows: achromatizing lens (mean +0.04 ± 0.20 D; range, -0.11 D to +0.35 D), doublet (mean +0.26 ± 0.18 D; range +0.09 to +0.54 D) and triplet (mean +0.02 ± 0.20D; range -0.23 to +0.30 D). In Experiment 3, changes were: doublet (DAA +0.15 D; PG +0.25 D) and triplet (DAA -0.19 D; PG +0.06 D) components. In-focus wavelengths were estimated by finding where the individual differences for in-focus positions between the doublet and triplet conditions matched the individual differences in longitudinal chromatic aberrations between the doublet and triplet conditions. The in-focus wavelengths were estimated to be between 575 nm and 635 nm (DAA 635 nm and 618 nm, PG 589 nm, HG 575 nm, AMS 580 nm, AK 630 nm and AJZ 610 nm).

Vimal, Pokorny and Smith[17] demonstrated that spectral lights (1.5° diameter semicircle) appear desaturated after steady continuous viewing and hue shifts are toward longer and shorter wavelengths for wavelengths between 586-670 nm and 546-570 nm, respectively. In this study, the short wavelength (532 nm) light appeared desaturated already at best focus, consistent with Vimal et al.,[17] but the small red light did not change appearance until defocused. Vimal et al. suggested that the change in appearance involved a post-receptoral locus, as receptoral adaptation would cause a shift along the spectral locus due to changes in quantal catch in L- and M-cones. Longitudinal chromatic aberrations can affect color signals at post-receptoral sites by altering physiological response of PC-cells as measured in dichromatic marmosets.[22] At high spatial frequencies, longitudinal chromatic aberration decreases the effective contrast of out-of-focus wavelengths (e.g. in an red-green equiluminant grating),[21] and can introduce luminance artifacts signaled by the PC-pathway[22]. With broad band spectra, the effect of longitudinal chromatic aberration on the M-cone fundamental is significant, resulting in a loss of cone contrast.[23]

In conclusion, longitudinal chromatic aberrations, but not monochromatic aberrations, are involved in changing the appearance of small (1’ arc) continuously viewed narrow band lights with defocus. The context is important as this phenomenon did not occur when the small black annulus was removed. L/M cone ratio does not affect the phenomenon. That the reported change in color appearance with defocus is not consistent with the in-focus color names implies there must be additional defocus dependent neural mechanisms contributing to the change in color appearance because defocus does not change the spectral properties of the light. These results have practical implications as there are transport situations in which optical defects of the eye can affect the correct recognition of small lights (e.g. rail and aviation).

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David A. Atchison can be reached by e-mail at d.atchison@qut.edu.au and Andrew J. Zele can be reached by e-mail at andrew.zele@qut.edu.au

FIGURE CAPTIONS

Fig. 1. A. Representation of stimulus (not to scale); angles are relative to the eye. B. Arrangement of components for generating the stimulus (not to scale).

Fig. 2. Representation of the optical system. A_1 - aperture conjugate with the participant's pupil; A_2 - field stop (5°); lenses L_1-L_4; mirrors M_1-M_6 with M_3-M_6 forming an optical trombone; TF - trial lenses; AC - lenses manipulating chromatic aberration; H - hot mirror; LED – infrared LEDs.

Fig. 3. Group average (n = 7) longitudinal chromatic aberration (4 mm) for four lens conditions. To obtain the plots for each lens condition, the individual participant results were shifted vertically to minimize the variance in chromatic aberration of the group data across the wavelength range. Error bars indicate standard deviations.

Fig. 4. Adaptive optics system for Experiment 2. See text for details.

Fig. 5. Defocus producing change in appearance of the red light for the different lens conditions in Experiment 1. Results for each participant were manipulated so that the in-focus for 4 mm diameter was zero. Only 2/7 participants saw the change in appearance with the 2 mm pupil and only 5/7 with the triplet condition. Errors bars show standard deviations.

Fig. 6. Defocus producing change in appearance of the red light without and with adaptive optics correction of monochromatic aberrations at 4 mm and 6 mm pupil sizes in Experiment 2. Results for each participant were manipulated so that the in-focus for 4 mm diameter was zero. Errors bars show standard deviations.

Fig. 7. Minimum defocus producing maximum change in appearance of the 532 nm light with the different lens conditions for A) DAA and B) PG. The results for each participant were manipulated so that the in-focus condition was zero. Errors bars show standard deviations.

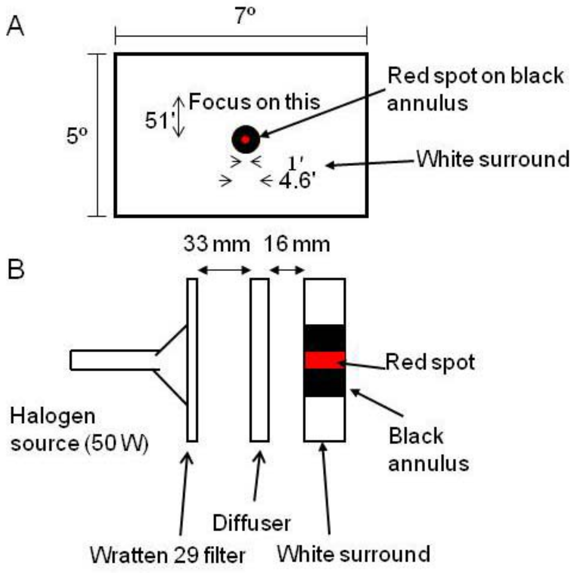
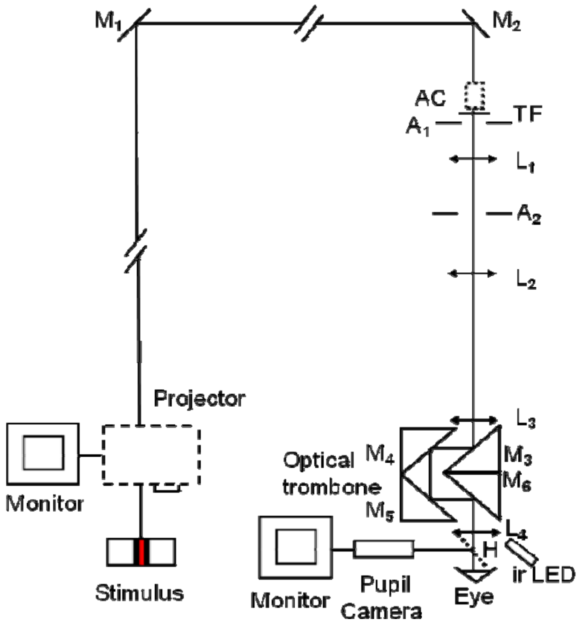

A
7°
5°
51'
Focus on this
Red spot on black annulus
1'
4.6'
White surround
B
33 mm
16 mm
Red spot
Halogen source (50 W)
Black annulus
Diffuser
Wratten 29 filter
White surround

Fig. 1


M_1
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M_4
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Monitor
Pupil Camera
Eye

Fig. 2

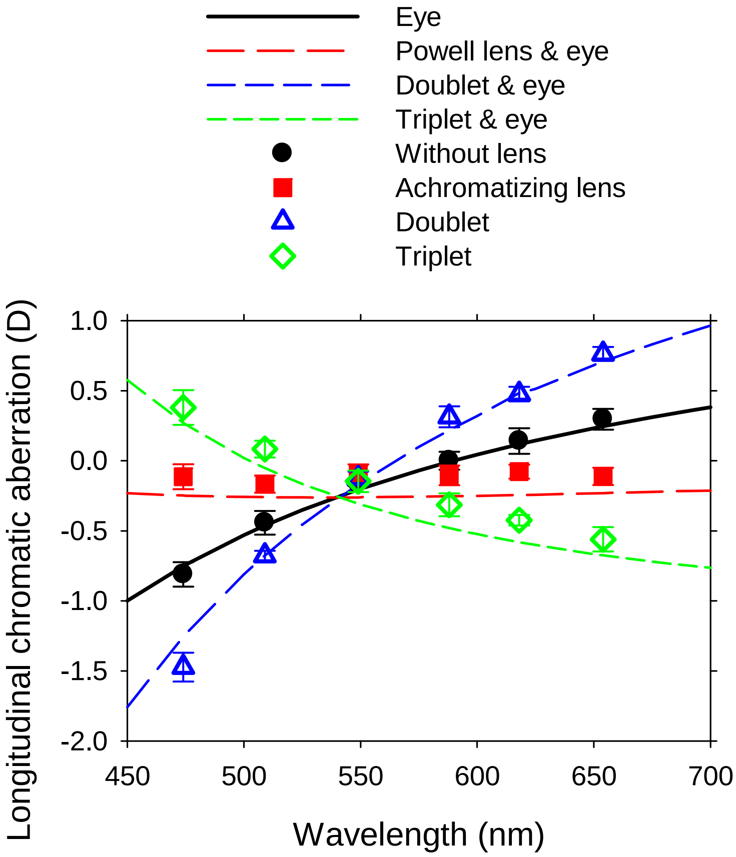
Eye
Powell lens & eye
Doublet & eye
Triplet & eye
Without lens
Achromatizing lens
Doublet
Triplet
Longitudinal chromatic aberration (D)
1.0
0.5
0.0
-0.5
-1.0
-1.5
-2.0
450
500
550
600
650
700
Wavelength (nm)

Fig. 3

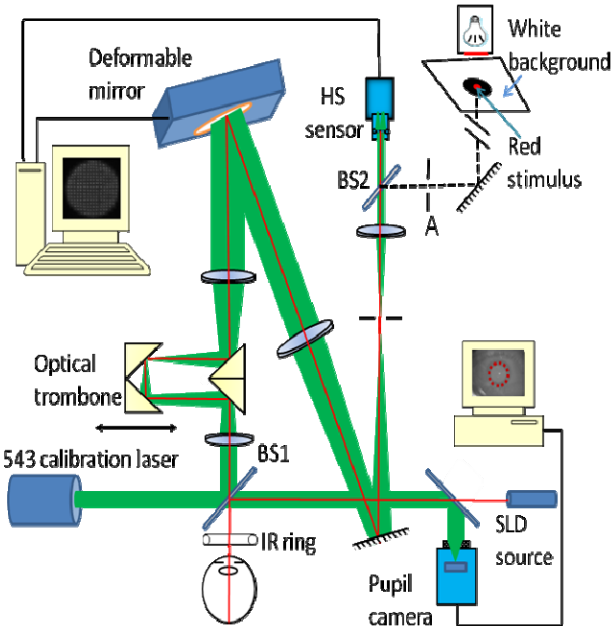
Deformable mirror
HS sensor
White background
Red stimulus
BS2
A
Optical trombone
543 calibration laser
BS1
IR ring
Pupil camera
SLD source

Fig. 4

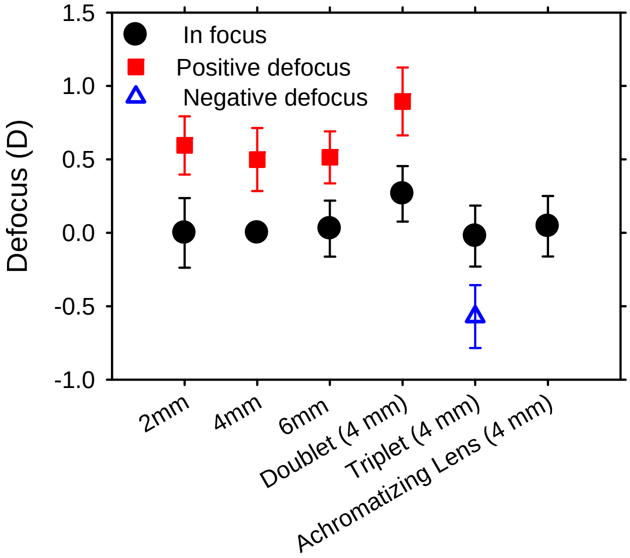
Defocus (D)
1.5
1.0
0.5
0.0
-0.5
-1.0
In focus
Positive defocus
Negative defocus
2mm
4mm
6mm
Doublet (4 mm)
Triplet (4 mm)
Achromatizing Lens (4 mm)

Fig. 5

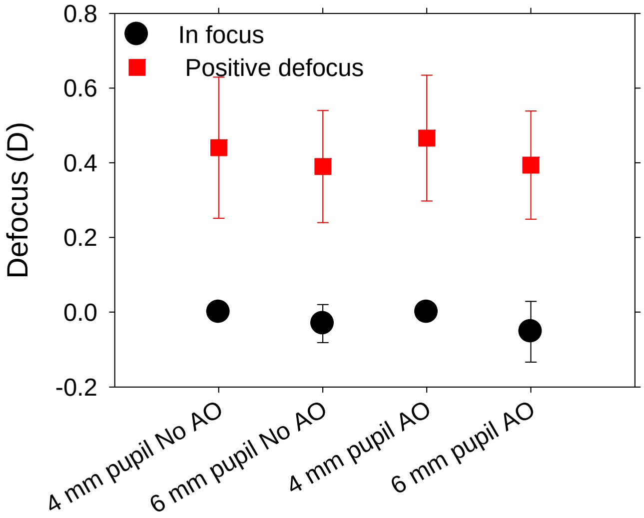
0.8
0.6
0.4
0.2
0.0
-0.2
Defocus (D)
In focus
Positive defocus
4 mm pupil No AO
6 mm pupil No AO
4 mm pupil AO
6 mm pupil AO

Fig. 6

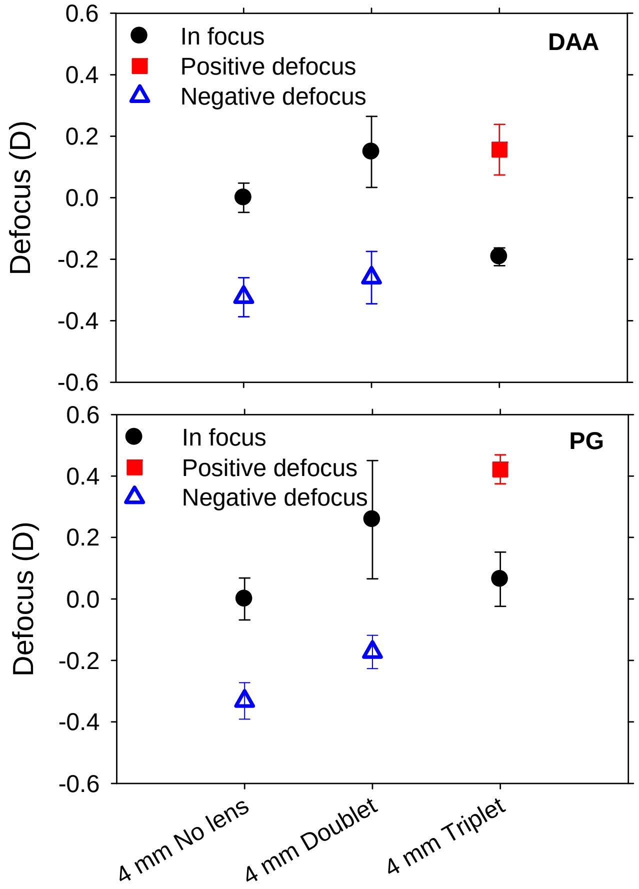
0.6
0.4
0.2
0.0
-0.2
-0.4
-0.6
Defocus (D)
In focus
Positive defocus
Negative defocus
DAA
PG
4 mm No lens
4 mm Doublet
4 mm Triplet

Fig. 7

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