Spectral bandwidth and ocular accommodation

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Received April 13, 1994; revised manuscript received October 4, 1994; accepted October 4, 1994

Previous studies have suggested that targets illuminated by monochromatic (narrow-band) light are less effective in stimulating the eye to change its focus than are black–white (broadband) targets. The present study investigates the influence of target spectral bandwidth on the dynamic accommodation response in eight subjects. The fixation target was a 3.5-cycle/deg square-wave grating illuminated by midspectral light of various bandwidths [10, 40, and 80 nm and white (CIE Illuminant B)]. The target was moved sinusoidally toward and away from the eye, and accommodation responses were recorded and Fourier analyzed. Accommodative gain increases, and phase lag decreases, with increasing spectral bandwidth. Thus the eye focuses more accurately on targets of wider spectral bandwidth. The visual system appears to have the ability to analyze polychromatic blur to determine the state of focus of the eye for the purpose of guiding the accommodation response.

Key words: Aberration, accommodation, bandwidth, blur, chromatic, focus, retinal image, spectral, wavelength

1. INTRODUCTION

Accommodation is the process by which the eye focuses objects in response to changes in viewing distance. Although studies have shown that perceived distance,[1,2] cognitive demand,[3] and voluntary effort[4,5] contribute to the accommodation response, the eye accommodates with remarkable accuracy even when these cues are eliminated.[6] This implies that optical (dioptric) stimuli for accommodation (e.g., blur produced by defocus) are important for driving accommodation.

Blur has been regarded by several investigators as the primary optical stimulus for accommodation.[7–10] Yet blur of a monochromatic (narrow-band) target is not an effective stimulus for accommodation.[11–14] This implies that the visual system obtains certain information about the state of focus of the eye from the blurred image of a polychromatic target and that such information is absent in monochromatic light. Crane[15] proposed that, in the presence of chromatic aberration, the three photoreceptor mechanisms of the eye, with their individual spectral sensitivity functions, sample the polychromatic retinal image at three levels of focus. As a natural consequence of longitudinal chromatic aberration, contrast of the retinal image is maximum for the wavelength in focus such that if long-wave light is in focus, image contrast is maximum at long wavelengths and is reduced for short-wavelength light.[16] It seems plausible that a comparison of image contrast between two wavebands could yield information (encoded as neural signals) that represents the state of focus of the eye. In a computational model, Flitcroft[17] suggests that spatially antagonistic, color-opponent cells might form a substrate for comparing contrast in different wavebands to monitor the focus of targets of intermediate spatial frequency [2–8 cycles per degree (cyc/deg)].

In the present study we illuminated a grating target by light of four nominal spectral bandwidths [10, 40, and 80 nm and broadband white (CIE Illuminant B)] to determine whether targets of progressively wider spectral bandwidth encourage more-accurate accommodation. We analyzed the nature of the blur spread function for targets of increasing spectral bandwidth after considering the effects of the photopic spectral sensitivity of the eye and longitudinal chromatic aberration.[18,19]

2. METHODS

The eight subjects were young adults with normal color vision (Nagel anomaloscope) and 20/20 corrected Snellen acuity. A 3.5-cyc/deg square-wave grating target was presented to the subject's eye in a Badal optical system[20] so that changes in target distance altered focus without affecting the size or illumination of the target.[21] The grating was a Ronchi ruling, illuminated by broadband white light (4874-K CIE Illuminant B) or by bandpassed light produced by the introduction of interference filters (10, 40, and 80 nm) in front of a tungsten–halogen source. Target luminance was equalized by a neutral-density wedge. An aerial image of the target moved sinusoidally toward and away from the Badal lens to stimulate the eye to change its focus. Accommodation of the eye was monitored by a high-speed infrared optometer,[22] and the data were analyzed by a fast Fourier transform (FFT). Gain and phase lag of the response at the temporal frequency of target motion (0.2 Hz) served as an index of accommodative performance to the various spectral targets.

A. Optical System

The optical system used for presenting targets and stimulating accommodation is described in Fig. 1. The recording optometer was described previously[22] and is represented in Fig. 1 as a rectangle (IR OPT).

1. *Illumination Optics (Dashed Lines)*

Light from a tungsten–halogen source (3200 K) was filtered by a Kodak (80 B) color-compensating filter to produce light of a higher color temperature (CIE Illumi-

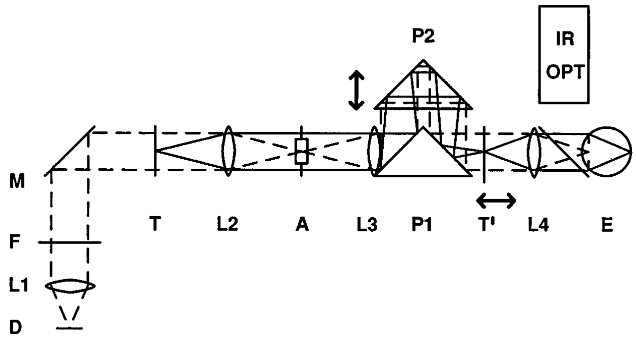

Fig. 1. Schematic of the Badal optical system for stimulating accommodation of the eye (E). Dashed lines show the optical path from the source of illumination, and solid lines represent target optics. Interference filters of three bandwidths (10, 40, and 80 nm) could be introduced at F to alter the spectral composition of a square-wave grating target (T). The sinusoidal motion of prism P2 moved an aerial image of target T′ toward and away from the Badal lens (L4) through a range of 1.0 D.

nant B, 4874 K),[23] and the light source was imaged onto an opal diffuser (D). Light from a circular patch on the diffuser was collimated by lens L1, and interference filters of various half-peak bandwidths (10, 40, and 80 nm) were introduced to alter the spectral bandwidth of the source. The collimated beam was deflected by a mirror (M) and illuminated a grating target (T) from behind. Lens L2 formed an image of the source in the plane of a 12-mm aperture (A). Lenses L3 and L4 together imaged the source in the plane of the subject's pupil (Maxwellian view). Aperture A was imaged by these lenses (L3 and L4) as a 3-mm artificial pupil. Light rays of the illumination system remained collimated as they reflected off the mirrored surfaces of prisms P1 and P2.

2. Target Optics (Solid Lines)

The target was a Ronchi ruling oriented vertically, presented in a 6-deg circular field with blurred margins. Rays from target T (Fig. 1) were collimated by lens L2 and focused by lens L3 to form an aerial image at T′ after reflection off mirrored prisms P1 and P2. The position of the aerial image (with regard to Badal lens L4) could be altered by movement of prism P2 toward or away from prism P1, as shown by the arrows. Prism motion was controlled by computer and synchronized with the data acquisition. The subject's eye was positioned with the pupil plane at the second principal focus of the Badal lens ($f = 10$ cm) by viewing of the first Purkinje image of the target in a telescope (not shown). Each centimeter of target motion (T′) generated a 1.0-D change in optical vergence at the eye.

B. Spectral Bandwidths

Two definitions of spectral bandwidth have been employed in the present study. For the interference filters used, the manufacturer's specifications were used, and these are defined as the wavelength interval at half-peak transmittance. For the analysis presented in the discussion (Section 4 below), bandwidth is defined as wavelength interval at $1/e$ of peak normalized luminance. Four bands of light were used for illuminating the target. Light from the source (4874 K) was passed through interference filters (peak transmittance at 550 nm) to create the spectral bands depicted in Fig. 2. Luminance of the targets was measured through the Maxwellian-view system[21] by a Pritchard photometer and maintained at 80 cd/m^2 by a neutral-density wedge.

C. Procedures

Subjects were positioned on a bite plate assembly to stabilize the head and to facilitate alignment. The target moved sinusoidally toward and away from the subject's eye at a temporal frequency of 0.2 Hz with a peak-to-peak amplitude of 1.0 D, around a mean level of 2 D. Subjects were instructed to look at the center of the grating and to pay undivided attention to the target. A temporal frequency of 0.2 Hz was used because at higher temporal frequencies gain declines substantially,[6,13] thereby reducing the signal-to-noise ratio, whereas at lower temporal frequencies voluntary accommodation is more likely to have some influence on the response.

Each accommodation trial lasted 40.96 s, yielding an array of 4096 (2^{12}) data points at a sampling rate of 100/s. We chose 40.96 s (as opposed to 40 s) because of constraints posed by the FFT procedure, which required an array size that is an integer power of 2. During each trial eight sinusoidal cycles of target focus were presented monocularly. Subjects were allowed to blink but were instructed not to use blinks in an attempt to improve the perceptual clarity of the target. Most subjects did not blink more than three or four times, and data with excessive blinks (e.g., produced by tearing) were rejected. Blinks produced high-amplitude transient artifacts in the data that were eliminated by filtering if their velocity exceeded 12 D/s. The four spectral conditions (10, 40, and 80 nm and white) were presented five times to each subject in random order. Gain and phase lag of accommodation for each trial were obtained by Fourier analysis (FFT) and were vector averaged for each condition. Analysis-of-variance and *post hoc* multiple comparison procedures were applied to the mean gain and phase data ($n = 8$) for a within-subject experimental design.

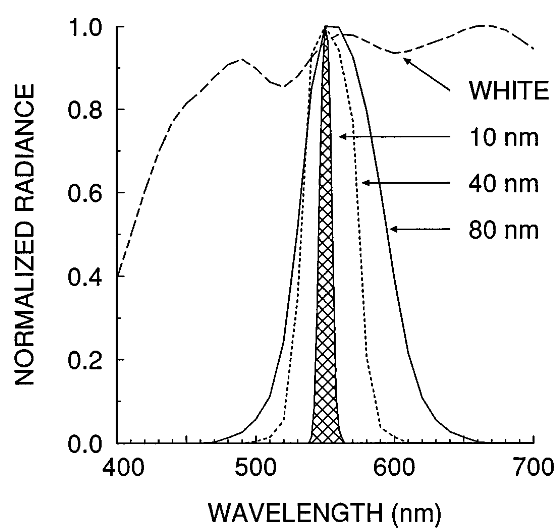

Fig. 2. Spectral distributions of the four test conditions (10, 40, and 80 nm and white) normalized to their individual peaks. The bandwidths specified here are nominal in that they refer to the filter manufacturer's specifications of bandwidth at half-peak transmittance.

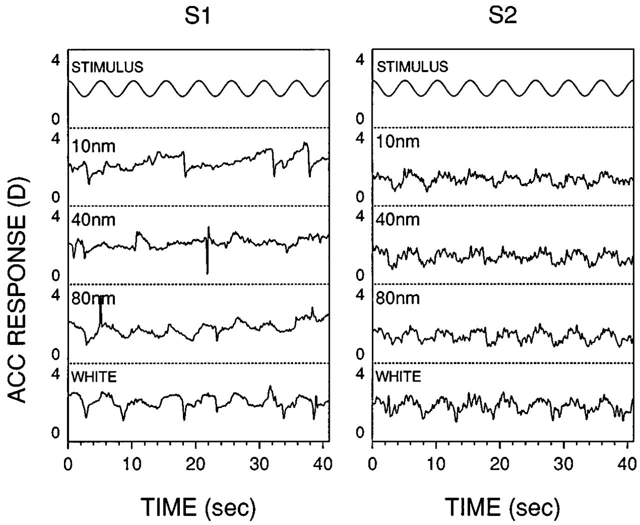

Fig. 3. Accommodation responses to the four target conditions for two subjects. The uppermost trace (stimulus) shows sinusoidal target motion (0.2 Hz, 1-D amplitude) toward and away from the Badal lens. The response traces represent accommodation to a 3.5-cyc/deg square-wave grating target illuminated by light of a specified spectral distribution (Fig. 2). The two subjects shown here are not typical but rather depict extremes of the range of accommodative behaviors observed in the present study.

3. RESULTS

Accommodation responses to the four target conditions (10, 40, and 80 nm and white) are plotted for two subjects (S1 and S2) in Fig. 3. These two subjects represent the extremes of the range of accommodative behaviors exhibited by the sample (eight subjects in all). Notice that the high-frequency oscillations of accommodation are more pronounced for subject S2 than for subject S1 for all conditions. Another notable difference is that the response of subject S1 to the 10-nm condition shows some time periods during which little or no accommodative tracking is evident, whereas subject S2 exhibits reasonable tracking ability in this condition (10 nm), albeit of reduced amplitude and longer phase lag than for the white target. For both subjects the amplitude of the response increases progressively as the bandwidth of light illuminating the target is increased, suggesting that accommodation is facilitated for targets of wider spectral bandwidth. It is apparent from these raw data (Fig. 3) that the natural high-frequency oscillations of accommodation make it somewhat difficult to judge the accuracy of the accommodation response. To make a quantitative assessment of the data, gain and phase lag of the response at the temporal frequency of the stimulus (0.2 Hz) were computed (FFT) and were vector averaged for the five trials from each subject.

Gain and phase lag for two typical subjects are plotted in Fig. 4. Error bars represent one standard error on either side of the mean for five data trials per condition. It is clear from these data that, despite individual differences, the gain of accommodation increases and the phase lag decreases as the spectral bandwidth of the illumination is changed from narrow-band (10 nm) to broadband (white).

Average gain and phase lag (Fig. 5) demonstrate the effect of spectral bandwidth on accommodative function in a group of eight subjects. Univariate analysis of variance shows that the gain of accommodation differs significantly across spectral bandwidth [$F(3, 21) = 42.3$, $p < 0.001$], as does the phase lag [$F(3, 21) = 17.9$, $p < 0.001$]. A conservative multiple comparison test (Tukey HSD) between means illustrates that gain increases significantly between successive progressive increases in bandwidth ($p < 0.05$), except for the 40- and 80-nm pair of conditions. However, mean phase lags of accommodation for

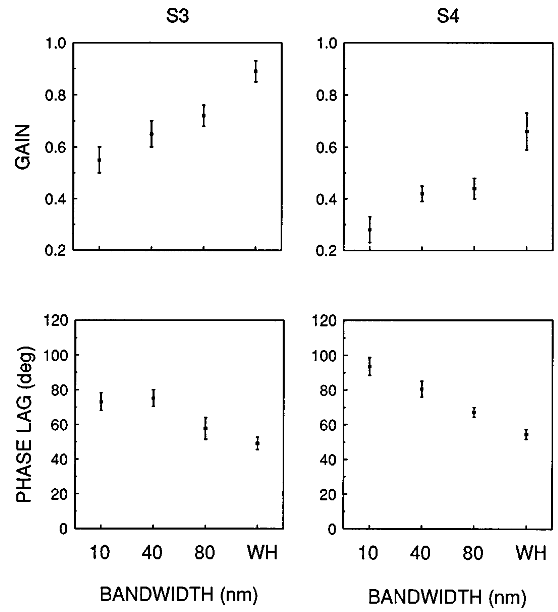

Fig. 4. Gain and phase lag of accommodation as a function of the spectral bandwidth of the target for two typical subjects, determined by a vector average of five trials per condition. The gain is an amplitude ratio (response/stimulus), and the phase lag is a time lag of the response with regard to the stimulus. As the target's spectral bandwidth increases, accommodative gain improves and phase lag declines.

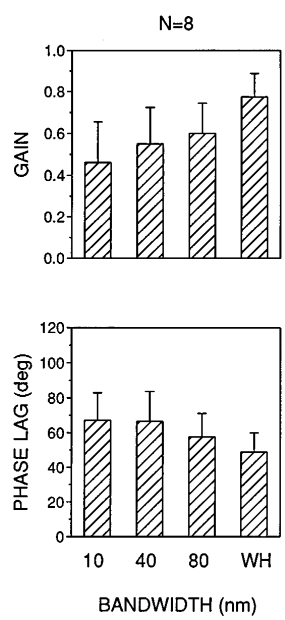

Fig. 5. Average gain and phase data for eight subjects to each of the four spectral conditions (10, 40, and 80 nm and white). Accommodative gain increases and phase lag decreases with increasing spectral bandwidth.

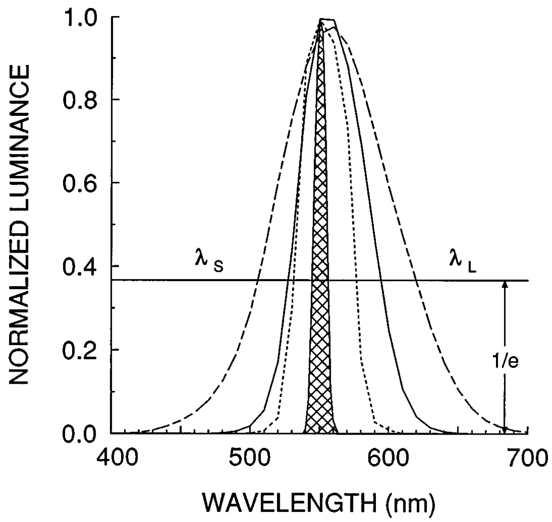

Fig. 6. Effective spectral distribution of the test conditions computed by multiplication of the photopic spectral sensitivity function of the eye by the functions depicted in Fig. 2. The horizontal line is $1/e$ height for these effective wavebands. The points of intersection of the $1/e$ line with the wavebands in the short-wave region (below 550 nm) are designated λ_S, and those in the long-wave region are represented by λ_L. Numerical values for λ_S and λ_L are given in Table 1.

these two conditions are significantly different ($p < 0.05$). Average phase data also differ at the 0.05 level for all pairs of conditions, excluding the 10- and 40-nm bands, to which the gain data were significantly different.

4. DISCUSSION

Taken together, the present results indicate that a wider spectral bandwidth of illumination allows the visual system to focus more accurately. From an ecological standpoint this does not come as a surprise because natural objects possess broad spectral reflectance functions,[24] and the eye is seldom confronted with narrow-band light. Even the spectral distributions of colorful objects can be relatively broadband.[24] When sunlight reflects diffusely from these objects, the retinal image is composed of light of a spectrum of wavelengths. Thus it seems reasonable to speculate that the visual system might have evolved focusing mechanisms that operate best in the presence of broadband illumination.

Spectrally broadband targets, when imaged by the optics of the eye, produce a complex retinal image that can be thought to consist of a series of image planes, one image plane for each wavelength of light. These image planes are displaced axially by an amount that depends on the longitudinal chromatic aberration of the eye and on the particular wavelengths in question. In addition, the effects of chromatic aberration are altered by the spectral sensitivity of the eye,[23,25] which declines substantially at the extremes of the visible spectrum. To help to illustrate the effects of chromatic aberration, we multiplied the spectral luminous efficiency function of the eye (CIE: 1931[25]) by the normalized spectral radiance of the four targets used in the experiment. As a result, the bandwidths of the stimuli are reduced, most notably for the white target, which now appears as a bandpass function (see Fig. 6).

Two extreme wavelengths (λ_S and λ_L) were chosen for each of the four wavebands, based on the $1/e$ height of the functions shown in Fig. 6. Dioptric vergence at the retina was computed for each wavelength[17] and is presented in Table 1. For the present experiment the chromatic difference in focus between λ_S and λ_L can be regarded as the ocular longitudinal chromatic aberration (LCA) present in each of the four targets. Figure 7 illustrates the effects of chromatic aberration on the retinal image of a luminance border (edge) for each of the four wavebands of light when the longer wavelength (λ_L) is in focus. Nominal values for bandwidth (10, 40, and 80 nm and white) have been retained in the figure. Real values

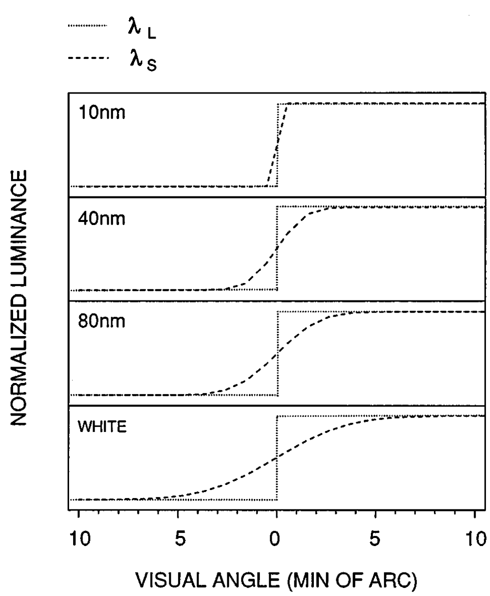

Fig. 7. Effect of increasing spectral bandwidth on the blur-spread function (of a luminance edge) for an eye with a 4-mm pupil. The longer wavelength (λ_L) of each spectral condition is in focus (dotted curves), and the shorter wavelength (λ_S) is out of focus (dashed curves) by an amount dependent on the longitudinal chromatic aberration produced by light of these two wavelengths.

Table 1. Optical Vergence and LCA for Each of the Four Spectral Wavebands at Two Extreme Wavelengths, λ_L and λ_S

Bandwidth (nominal)	λ_L Wavelength (nm)	λ_L Vergence (D)	λ_S Wavelength (nm)	λ_S Vergence (D)	$\lambda_L - \lambda_S$ Wavelength (nm)	$\lambda_L - \lambda_S$ LCA (D)
10 nm	556	−0.123	544	−0.199	12	0.076
40 nm	576	−0.010	531	−0.288	45	0.278
80 nm	594	+0.081	526	−0.324	68	0.405
White	619	+0.191	505	−0.490	114	0.681

for λ_S and λ_L and for $1/e$ bandwidth $(\lambda_L - \lambda_S)$ are tabulated (Table 1) along with the dioptric vergence and the amount of chromatic aberration.

The dashed curves in Fig. 7 show the luminance distribution of λ_S when λ_L (dotted curves) is in focus on the retina. The defocus of λ_S with regard to λ_L (Table 1, rightmost column) was used to find the standard deviation (in minutes of arc) of a Gaussian point-spread function, by the methods of Fry,[26] for a schematic eye with a 4-mm pupil. The edge-spread functions of Fig. 7 represent the definite integral of the point-spread function for the tabulated amounts of LCA. The type of blur depicted in Fig. 7 is a natural consequence of longitudinal chromatic aberration in an eye with a pupil of 4-mm diameter. All subjects in the study had pupils larger than 3 mm, and the choice of a 4-mm pupil (for Fig. 7) is arbitrary. Larger pupils result in wider edge-spread functions, and smaller pupils (e.g., 2 mm) reduce the blur produced by LCA.

Although the difference in ocular focus between the ends of the visible spectrum is substantial[18,19] (2D or more), even the relatively small amounts of chromatic aberration used for the present analysis produce a significant decline in the slope (contrast) of the edge-spread function. The width of the effective edge-spread function (including V_λ) for the 40-nm band of light is ~4 arcmin, and for white light it is approximately 10 arcmin. It is important to note that Fig. 7 has been generated strictly for the purpose of illustrating the fact that, even after the severely band-limiting effects of V_λ are included, the chromatic aberration of the eye has a notable effect on the blur profile of a luminance edge.

Results of the present experiment are in agreement with studies indicating that the visual system has the capacity to detect blur produced by chromatic aberration at luminance edges.[11–14] The three cone types of the retina, with their individual spectral sensitivity functions, effectively sample the retinal image at three different levels of defocus, corresponding to their wavelengths of peak sensitivity[15] or perhaps to a weighted average including the radiance distribution of the image.[17] It seems plausible that a comparison of retinal image quality between cone types, possibly through spatially bandpass, color-opponent pathways, could generate a neural signal that varies in proportion to ocular defocus and that could be used to direct accommodation. However, further research is necessary to confirm the involvement of color-opponent mechanisms in the control of accommodation to defocus of polychromatic targets.

In the present investigation the accuracy of dynamic accommodation was influenced significantly by incremental changes in target spectral bandwidth. Our findings agree with the results of studies done concurrently by other investigators who used different stimulus parameters.[12] Previous investigators[10] seem to disagree with the view that spectrally bandpass light (and thereby reduced ocular LCA) impairs accommodation, and the reasons for this discrepancy are not entirely clear. One possible explanation is that previous investigators tested this issue by using stationary targets (stimulus–response function), and they may have trained their observers to accommodate voluntarily. Those authors reported on one naïve subject (aged 20 years) who showed poor accommodation to spectrally bandpass (red or blue) targets (Ref. 10, Fig. 2f, p. 462); however, they disregarded these data as an artifact of inadequate training. They noted that "Training and motivation undoubtedly also play an important role, as is illustrated by subject (f), a secretary chosen to typify effects found with untrained observers. She evidently failed to respond at all to the lens-induced, higher target vergences." After reinstructing this subject ("careful explanation of the nature of the experiment"), the authors reported that she too could focus in monochromatic light. They reported a similar initial inaccuracy of accommodation for other naïve subjects to red or blue targets,[10] but their conclusions were based on the results obtained from trained observers. In the present experiment two of the authors served as subjects, while the remaining six were naïve to the purpose of the experiment. We find that trained observers respond in the same way as naïve subjects to moving targets, and we have used moving targets in our experiments to minimize the influence of voluntary accommodation. A systematic study of the effect of training is in order, but it must be conducted by use of both stationary and moving targets.

The effects of ocular chromatic aberration are usually dismissed as being small and not significant enough to influence visual mechanisms.[27,28] It is generally argued that, if a midspectral wavelength (say, 555 nm) is in focus, the spectral sensitivity of the eye reduces the effective chromatic aberration to very small amounts (0.15 D),[28] which may lie within the depth of focus of the eye. However, the oscillations of accommodation[29,30] are constantly changing the wavelength in focus, and, when a target moves toward or away from the eye, once again a new wavelength comes into focus. In fact the natural lag of accommodation to near targets and the lead of accommodation to far targets[31] also change the wavelength in focus. In the present study the 40-nm condition produced only 0.278 D of LCA; however, even such small amounts of LCA produce substantial facilitation of dynamic accommodation (see Section 3).

The data (Figs. 3–5) and the statistical analysis (Tukey HSD test) indicate that successively wider bands of target illumination produce an incremental improvement in accommodative performance. The bandwidth at which accommodative performance is the same as that for white is difficult to identify from these data mainly because the response to a white target (CIE Illuminant B) is significantly better than accommodation to the 80-nm bandpass target. The improvement in gain (and reduction in phase lag) from the 80-nm to the broadband white condition indicates the involvement of short-wavelength-sensitive cones in the analysis of the blur-spread function. Although the notion of accommodative control by individual cone types[15] (or by comparisons of image quality between cone types mediated by color-opponent cells[17]) is attractive, more experimental evidence is required.

The present investigation supports the view that the visual system has mechanisms for utilizing chromatic aberration as a source of information about the state of focus of the eye, and it uses this information to guide the accommodation response. These mechanisms could operate at levels close to the thresholds for chromaticity discrimination[32–34] and contrast-decrement sensitivity.[35] Further research is needed to uncover the neural substrate for the observed sensitivity of the eye–brain system to blur produced by polychromatic targets in the presence of ocular longitudinal chromatic aberration.

ACKNOWLEDGMENTS

This research was supported by grants from the National Eye Institute (EYO7494, EYO8953, EYO5901) and by a postdoctoral fellowship (F 32 EYO6403-02) awarded to K. R. Aggarwala. We thank Dean Yager, Milton Katz, and Jordan Pola for their helpful suggestions, John Orzuchowski and Mathew Polasky for technical assistance, and Jong Park for assistance with data collection.

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