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**Does Display Phosphor Bandwidth
Affect the Ability of the Eye to Focus?
(Reprint)**

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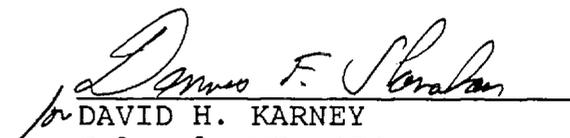
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Does display phosphor bandwidth
affect the ability of the eye to focus?

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ABSTRACT

The focusing response of the eye (accommodation) is degraded in monochromatic light for many subjects. To find out whether this degradation also occurs in narrowband polychromatic light, we measured the accommodation of nine young adult volunteer subjects across three bandwidths (10, 20, and 80 nm) and a broadband control (white light). The peak wavelength was 550 nm for each of the bandpass filtered stimuli, and the luminance of all targets was 10 cd/m². Accommodation was measured with a dynamic infrared optometer while the subjects viewed threshold-size, high-contrast letters under both dynamic and steady-state conditions. In the former, the optical distance of the target was varied sinusoidally from 0.0 to 2.0 diopters (optical infinity to 50 cm) at a temporal frequency of 0.5 Hz, while in the latter it was held constant at 1.0 diopter (1.0 m). We found that, under dynamic conditions, accommodative accuracy steadily improved in a statistically significant way with increases in spectral bandwidth. Under steady-state conditions, there was no statistically significant trend. These results suggest that accommodation might suffer from the use of narrowband phosphors in helmet-mounted displays under dynamic conditions, i.e., the observer might accommodate inaccurately to the display if frequent changes in focus to and from the display are required.

1. INTRODUCTION

The focusing response of the eye (accommodation) is degraded in monochromatic light for many subjects.¹⁻⁷ This is thought to occur because monochromatic light eliminates the colored fringes which are the result of the eye's longitudinal chromatic aberration, and which are believed to provide a directional cue for accommodation.¹⁻⁷ We do not know whether this degradation of accommodation is limited to monochromatic light, or whether it also occurs in narrowband polychromatic light, such as that emitted from the phosphors of monochrome displays. Inaccurate accommodation is significant with helmet-mounted displays because it results in decreased retinal-image contrast, which degrades resolution and a variety of other visual functions. To determine whether narrowband displays degrade accommodation, we

chromatically bandpass filtered broadband light and measured accommodation as a function of bandwidth.

2. METHODS

2.1 Experimental design and definitions

We recorded accommodation under both dynamic and static conditions. For the dynamic condition, we sinusoidally varied the optical vergence of light from the target over time. When this happens, the accommodative response typically has the form of a sinusoid with the same temporal frequency as the stimulus, but not necessarily the same amplitude.⁸ The ratio of response to stimulus amplitude (gain) was used as an index of accommodative performance for the dynamic condition.⁸

For the static condition, the optical vergence of light from the target was held constant over time. When this happens, the accommodative response typically fluctuates about a mean or DC level that is seldom coincident with the dioptric level of the stimulus.⁹ The difference between stimulus and mean response amplitude, in such circumstances, is referred to as the steady-state error, and this difference was used as an index of accommodative performance for the static condition.¹⁰ For a given target distance, the steady-state error can be caused by either excessive or insufficient accommodation, depending on whether the resting point of accommodation is proximal or distal to the target position, respectively.¹⁰ To avoid inadvertent cancellation effects in the averaging of steady-state errors due to opposite signs, only the absolute values of these errors were used in this study (e.g., Table 3 below).

2.2. Apparatus to measure accommodation

Accommodation was measured with a dynamic infrared optometer,¹¹ which was integrated into a dual-Purkinje image infrared eyetracker.¹² The combination of the two devices enabled us to make continuous, precise (± 0.1 D) and objective measurements of accommodation which were unaffected by small horizontal and vertical eye movements.

2.3 Apparatus to stimulate accommodation

The sinusoidal variations in the dioptric power of the stimulus were made without altering its luminance or spatial frequency by a motorized optical system (stimulus deflector) which was attached to the eyetracker.¹³ The dynamic stimulus to accommodation was a 0.5 Hz sine wave with a DC-to-peak amplitude of 1 D, and a DC level of 1 D. The steady-state stimulus was 1 D. A beamsplitter permitted the subjects to view the target

through the stimulus deflector while accommodation was recorded by the optometer.

2.4 Apparatus for chromatic filtering

The fixation target, which was located 5.4 m from the stimulus deflector, was a Bailey-Lovie visual acuity chart with a Weber contrast of 98%. The chart was illuminated by a projector which had the proper combinations of neutral density and bandpass filters to produce equiluminant (10 cd/m^2) stimuli with bandwidths of 10, 20, and 80 nm, all with a peak wavelength of 550 nm. The projector also generated a broadband control, which had the same luminance as the bandpass stimuli, a bandwidth of about 250 nm, and a peak wavelength of 600 nm.

2.5. Procedures to record accommodation

Accommodation was measured in the left eye for 12.8 seconds per trial while the right eye was occluded. Each trial yielded 256 data points since the optometer output was digitized at 20 Hz. A fast Fourier transform was done on these 256 points to obtain amplitude. Three trials were run for each condition, and amplitude was averaged across the three trials. The steady-state means were obtained from the average of three trial means, each of which was computed by averaging the 256 data points that were collected per trial.

2.6 Procedures to prevent artifacts

Since the optometer used in this study is subject to artifacts from small pupils, the pupils of the subjects were dilated with two doses of 2.5% phenylephrine hydrochloride. The doses were administered at 5-minute intervals, and consisted of one drop each. In this dosage and concentration, phenylephrine has little or no effect on accommodation.¹⁴⁻¹⁵

The stimuli were presented in random order to prevent serial effects. The optometer output was routed through a lowpass analog filter to prevent aliasing. The filter had its -3 dB rolloff at 5 Hz, and produced 68 dB of attenuation at 7.5 Hz. A chin cup and forehead rest were used to prevent head-movement artifacts. The subjects were instructed to view threshold size letters using the same effort to maintain clarity as in reading a book.¹⁶ This was done to keep voluntary effort minimal and constant between subjects.

2.7. Subjects

Nine volunteer subjects, who gave their informed consent, were recruited for the study. The subjects, whose mean (\pm SD) age

was 23.3±2.6 years, ranged in age from 21 to 29 years. All subjects had unaided distance visual acuities of at least 20/20 in each eye and were free from eye disease and significant oculomotor dysfunction. Eight subjects had normal color vision, while one had a red-green color defect (protanomaly).

3. RESULTS

3.1 Statistical procedures

The effect of bandwidth on the dependent variables was analyzed with a univariate repeated measures analysis of variance. The assumption of sphericity was tested and the degrees of freedom adjusted when necessary using the Greenhouse-Geisser method.

3.2. Gain

Table 1 shows how gain varied with bandwidth. Although the gains were small for all bandwidths, this is typical for the stimulus frequency of 0.5 Hz.⁸ For individual subjects, gain generally increased monotonically with increasing bandwidth, with the notable exception of the only subject who was color defective. The color defective subjective showed no bandwidth-dependent effect.

Table 1.
Effect of bandwidth on gain.

Bandwidth (nm)	Gain (response/stimulus)			
	With color defective (n = 9)		Without color defective (n = 8)	
	Mean	SD	Mean	SD
10	0.15	0.08	0.15	0.08
20	0.18	0.08	0.17	0.08
80	0.21	0.07	0.20	0.08
Broadband	0.26	0.09	0.26	0.09

There was a statistically significant main effect for bandwidth regardless of whether the color deficient subject was included [$F(2.07, 16.53) = 23.56, p < 0.0001$] or excluded [$F(2.03, 14.21) = 35.36, p < 0.0001$]. Multiple comparisons were done with and without the data of the color deficient subject using the Newman-Keuls' method (Table 2). There was a statistically significant difference between gains at all bandwidths, even when the color defective subject was included. This suggests that there is a graded effect for bandwidth on gain, with no apparent asymptote.

3.3. Steady-state error

Steady-state error did not vary with bandwidth regardless of whether the color defective subject was included [$F(1.63, 13.04) = 1.44, p > 0.26$] or excluded [$F(1.69, 11.81) = 2.10, p > 0.16$]. Table 3 lists the steady-state means.

Table 2.

Multiple comparisons of gain cell means.

(* = statistically significant, BB = broadband)

Bandwidth pairs	With color defective (n = 9)		Without color defective (n = 8)	
	Test statistic	Difference between means	Test statistic	Difference between means
10, 20	0.025	0.023*	0.023	0.024*
10, 80	0.031	0.051*	0.028	0.056*
10, BB	0.034	0.099*	0.030	0.110*
20, 80	0.025	0.028*	0.023	0.033*
20, BB	0.031	0.076*	0.028	0.086*
80, BB	0.025	0.048*	0.023	0.054*

Table 3.

Effect of bandwidth on steady-state focus error.

(SD = standard deviation)

Bandwidth (nm)	Steady-state error (D)			
	With color defective (n = 9)		Without color defective (n = 8)	
	Mean	SD	Mean	SD
10	0.43	0.22	0.44	0.23
20	0.44	0.24	0.46	0.26
80	0.44	0.31	0.49	0.30
Broadband	0.51	0.31	0.54	0.32

4. DISCUSSION

4.1 Dynamic conditions

Our main finding is that accommodative gain depends upon the chromatic bandwidth of the stimulus under dynamic conditions. This bandwidth dependency supports the hypothesis that accommodation is at least partially under the control of chromatic mechanisms because luminance was kept constant across bandwidth in our experiment.¹⁷ This is probably why only the color defective subject did not exhibit the bandwidth effect.¹⁷

4.2 Static conditions

Steady-state error did not vary with bandwidth in our experiment. This is consistent with other investigators who found that accommodation does not seem to be influenced much by chromatic cues under static conditions.¹⁸⁻²¹ This may be because the sensitivity to chromatic contrast is severely reduced compared to the sensitivity to luminance contrast under low-velocity or static conditions.²²

4.3 Practical implications

The practical implication of these results is that narrowband display phosphors, such as the P43, probably do not impair accommodation when the observer is engaged in static viewing, such as in an office or laboratory. However, when an observer must frequently change focus from the display to objects

located in different focal planes, the ability of the eye to focus on the display may be decreased by narrowband phosphors. For example, a military helicopter pilot flying with a helmet-mounted display may have to rapidly alternate focus from the display to objects outside the aircraft to objects in the cockpit. Under such dynamic circumstances, a narrowband phosphor could promote less accurate focusing of the eye on the display. The end result could be impaired detection of hazards and targets.

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