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Vision Research 45 (2005) 1265–1274
Vision Research
www.elsevier.com/locate/visres

Accommodation with and without short-wavelength-sensitive cones and chromatic aberration

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Received 11 July 2004; received in revised form 8 November 2004

Abstract

Accommodation was monitored while observers (23) viewed a square-wave grating (2.2 cycles/deg; 0.53 contrast) in a Badal optometer. The grating moved sinusoidally (0.2 Hz) to provide a stimulus between −1.00 D and −3.00 D during trials lasting 40.96 s. There were three illumination conditions: 1. Monochromatic 550 nm light to stimulate long-wavelength-sensitive cones (L-cones) and medium-wavelength-sensitive cones (M-cones) without chromatic aberration; 2. Monochromatic 550 nm light + 420 nm light to stimulate long-, medium- and short-wavelength-sensitive cones (S-cones) with longitudinal chromatic aberration (LCA); 3. Monochromatic 550 nm light + 420 nm light to stimulate L-, M- and S-cones viewed through an achromatizing lens. In the presence of LCA mean dynamic gain decreased ($p = 0.0003$; ANOVA) and mean accommodation level was reduced ($p = 0.001$; ANOVA). The reduction in gain and increased lag of accommodation in the presence of LCA could result from a blue-yellow chromatic signal or from a larger depth-of-focus.

Keywords: Accommodation; Blur; Chromatic aberration; Defocus; Short-wavelength-sensitive cones

1. Introduction

The standard view of accommodation control is that luminance contrast provides the stimulus (Bobier, Campbell, & Hinch, 1992; Charman & Tucker, 1978; Heath, 1956; Phillips & Stark, 1977; Stark & Takahashi, 1965; Troelstra, Zuber, Miller, & Stark, 1964; Wolfe & Owens, 1981). Since blur from defocus reduces luminance contrast both for myopic and hyperopic defocus, the stimulus from defocus blur is an “even-error” signal without directional quality, and feedback from changes in defocus is an essential part of the accommodative process. However, several lines of evidence suggest that “odd-error” signals provide the sign of defocus for accommodation (Fincham, 1951; Flitcroft, 1990; Kruger, Mathews, Katz, Aggarwala, & Nowbotsing, 1997b; Lee, Stark, Cohen, & Kruger, 1999; Rucker & Kruger, 2004a; Smithline, 1974; Stark, Lee, Kruger, Rucker, & Fan, 2002b). Similarly experiments on animals show that signed error signals control the coordinated growth and development of axial length and optical components of the eye (Park, Winawer, & Wallman, 2003; Schaeffel & Diether, 1999; Smith & Hung, 1999; Smith, Hung, & Harwerth, 1994; Wildsoet & Schmid, 2001; Wildsoet & Wallman, 1995). We propose that the signed signals that control emmetropization also could control accommodation (Rucker & Kruger, 2001).

Fincham (1951) was the first to show that a chromatic signal from the longitudinal chromatic aberration

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0042-6989/$ - see front matter © 2004 Published by Elsevier Ltd.
doi:10.1016/j.visres.2004.11.017

(LCA) of the eye provides the sign of defocus for accommodation. He also suggested that a luminance signal from the angle of incidence of light reaching the retina distinguishes myopic from hyperopic defocus (Fincham, 1951). One possibility is that the directional sensitivity of cones (Stiles–Crawford effect Type 1) extracts the sign of defocus (Fincham, 1951; Kruger, López-Gil, & Stark, 2001; Kruger, Stark, & Nguyen, 2004; Stark, Kruger, & Atchison, 2002a) and monochromatic aberrations of the eye also could play a role (Chen, Kruger, & Williams, 2002; Fernandez & Artal, 2002; Wilson, Decker, & Roorda, 2002).

Most investigators have agreed with Fincham's findings regarding the chromatic signal from LCA (Aggarwala, Kruger, Mathews, & Kruger, 1995a; Aggarwala, Nowbotsing, & Kruger, 1995b; Flitcroft, 1990; Kotulak, Morse, & Billock, 1995; Kruger, Mathews, Aggarwala, & Sanchez, 1993; Kruger, Aggarwala, Bean, & Mathews, 1997a; Kruger, Mathews, Aggarwala, Yager, & Kruger, 1995a; Kruger, Nowbotsing, Aggarwala, & Mathews, 1995b; Kruger & Pola, 1986; Lee et al., 1999; Rucker & Kruger, 2004a; Stark et al., 2002b), but some investigations have provided contrary evidence (Bobier et al., 1992; Charman & Tucker, 1978; Stark & Takahashi, 1965; Troelstra et al., 1964; van der Wildt, Bouman, & van de Kraats, 1974). The reasons for the disagreement have been summarized by Kruger et al. (1997a), Lee et al. (1999) and Stark et al. (2002b).

Chromatic dispersion of light by the ocular media produces a chromatic-difference-of-focus across the visible spectrum that approaches 2.5 diopters between 380 nm and 760 nm. This results in a difference in contrast between the long- middle- and short-wavelength components of the broadband retinal image (Marimont & Wandell, 1994) that provides a signed chromatic signal for accommodation (Flitcroft, 1990; Kruger et al., 1995a). Although recent calculations show that monochromatic aberrations reduce the difference in contrast between the wavelength components of the retinal image especially when the pupil is large (McLellan, Marcos, Prieto, & Burns, 2002), experiments show that when the pupil size is moderate (3 mm) LCA provides an effective directional stimulus (e.g. Kruger et al., 1993, 1997a, 1997b; Kruger & Pola, 1986; Stone, Mathews, & Kruger, 1993). Since the rate of change in focus as a function of wavelength (LCA) is much larger for short-wavelength light than for long-wavelength light (Bedford & Wyszecki, 1957; Thibos, Ye, Zhang, & Bradley, 1992) the "chromatic-difference-of-contrast" per nanometer change in wavelength is larger for short-wavelength light than for longer wavelengths (Marimont & Wandell, 1994).

As a consequence of LCA the three cone types (long-, middle- and short-wavelength-sensitive cones) effectively sample the retinal image in three different focal planes (Crane, 1966). Thus a comparison of the cone-contrasts of the image, at a single plane of focus, could provide the sign of defocus (Flitcroft, 1990). In support of this view, dynamic accommodative gain (ratio of response amplitude to stimulus amplitude) increases monotonically when the spectral bandwidth of illumination is increased from narrowband monochromatic light to broadband white light (Aggarwala et al., 1995a; Kotulak et al., 1995). In addition, simulations of the effects of defocus and LCA drive accommodation in the predicted direction (Kruger et al., 1995a, Lee et al., 1999; Rucker & Kruger, 2004a; Stark et al., 2002b). These experiments support the notion that L- and M-cones extract a chromatic signal from the retinal image that provides the sign of defocus. Recently, Rucker and Kruger (2004a) altered L- and M-cone contrasts independently and found that the ratio of L-cone contrast to M-cone contrast significantly alters the mean level of accommodation. At both luminance and chromatic borders, high L-cone contrast combined with low M-cone contrast reduces accommodation for near, while high M-cone contrast with low L-cone contrast increases accommodation for near.

Since the rate of change of defocus is greater for short-wavelength light than for long-wavelength light, the participation of S-cones in the process might provide a stronger chromatic signal for accommodation than the response from a comparison of L- and M-cone contrasts. Rucker and Kruger (2001) isolated S-cones and showed that some subjects can accommodate using only S-cones; however the dynamic response (gain) from S-cones alone was smaller than the dynamic response from L- and M-cones together. In addition latencies and time-constants of accommodation to step changes in target vergence were significantly longer for S-cones alone than for LM-cones (Rucker & Kruger, 2004b). Thus the dynamic accommodation response from S-cones might be too slow to improve the directional signal from LCA. In the present experiment we examine dynamic accommodation at 0.2 Hz mediated by LM-cones with and without S-cones, both with and without LCA.

2. Methods

2.1. Subjects

Twenty seven subjects volunteered to participate in the experiment. Two subjects dropped out before data collection had been completed, and two subjects were eliminated during preliminary trials because they could not accommodate to the target in the Badal stimulus system. The remaining 23 subjects participated in the study and were paid for participation. All subjects had 6/6 visual acuity or better, normal color vision (Nagel anomaloscope and D-15 test) and no history of strabismus, amblyopia, ocular disease, injury, or surgery. Sub-