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Detection of the depth order of defocused images

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Abstract

The sign of an accommodative response is provided by differences in chromatic aberration between under- and over-accommodated images. We asked whether these differences enable people to judge the depth order of two stimuli in the absence of other depth cues. Two vertical edges separated by an illuminated gap were presented at random relative distances. Exposure was brief, or prolonged with fixed or changing accommodation. The gap was illuminated with tungsten light or monochromatic light. Subjects could detect image blur with brief exposure for both types of light. But they could detect depth order only in tungsten light with long exposure, with or without changes in accommodation.

Keywords: Depth perception; Blur detection; Accommodation; Chromatic aberration

1. Introduction

1.1. The stimulus for accommodation

The image of an object becomes increasingly blurred as the object is removed from the plane in which the eyes are accommodated. However, defocus blur in an aberration-free eye, does not indicate whether an out-of-focus object is nearer than or more distant than a fixated object. This is because the image of an object nearer than the plane of focus may be blurred to the same extent as that of an object beyond the plane of focus. Defocus blur, in an aberration-free eye is said to provide an even-error signal. Normally, when the eyes are converged and accommodated on an object, cues to relative depth such as perspective, overlap, parallax, and disparity indicate the direction and magnitude of the change in accommodation required when fixation is changed to another object. In the absence of such cues, the initial accommodative response could be made at random and then corrected if in the wrong direction. There are spontaneous fluctuations in accommodation of a few tenths of a dioptres at frequencies up to 3 Hz. Campbell and Westheimer (1959) found that subjects made many initial errors in responses to an out-of-focus image when cues to the direction of misaccommodation were eliminated. However, there are features of defocused images, other than blur, that vary according to whether the stimulus is nearer than or beyond the plane of focus. These features include chromatic aberration, off-axis spherical aberration, astigmatism, and the Stiles–Crawford effect. They could therefore provide an odd-error signal that could be used to indicate the direction of an accommodative response.

Longitudinal chromatic aberration produces color fringes on the image of an object that vary according to whether the eyes are under- or over-accommodated on the object. Thus, the image of a point of white light tends to be surrounded by a red fringe when the eyes are under-accommodated (hyperopic) and by a blue fringe when they are over-accommodated (myopic). Ivanoff (1949) first suggested that color fringes produced by longitudinal chromatic aberration might signify the sign of misaccommodation. Fincham (1951) found that, with a

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target illuminated with white light, all their subjects could change accommodation in the appropriate direction when a 1.0 D lens was placed before the eye. However, 60% of subjects were unable to accommodate in monochromatic yellow light, for which there is no chromatic aberration, or when the chromatic aberration was removed by an achromatizing lens. The subjects who could accommodate in monochromatic light must have used some other sign cue, such as spherical aberration.

Campbell and Westheimer (1959) found that, with the ciliary muscles paralyzed, subjects could learn to use a manual control to bring an object back into focus after it had been moved in depth. With white light, they moved the target in the correct direction on every trial. Some subjects failed in monochromatic light, showing that they had been using chromatic aberration. Other subjects performed correctly in monochromatic light but only in the presence of either spherical aberrations or astigmatism. Kruger, Aggarwala, Bean, and Mathews (1997) found that subjects maintained accurate and steady accommodation on a grating in white light but became unstable in monochromatic light, especially at the viewing distance of 5 D (20 cm). When chromatic aberration was optically reversed, accommodation at all distances became severely unstable and drifted from the correct state towards the state of dark accommodation. Stark, Lee, Kruger, Rucker, and Fan (2002) reported a similar result.

Aggarwala, Nowbotsing, and Kruger (1995) found that accommodative responses to a radial pattern moving sinusoidally in depth were much less regular under monochromatic light than under white light of the same luminance. Responses were also irregular with white light viewed through an achromatizing lens that neutralized the longitudinal chromatic aberration of the eyes. Kruger, Mathews, Aggarwala, Yager, and Kruger (1995) modulated the red, green, and blue chromatic components of a 3 cpd sinusoidal grating viewed through an achromatizing lens to simulate changes in chromatic aberration produced by moving the grating in depth. This evoked appropriate accommodative changes.

This evidence demonstrates that longitudinal chromatic aberration can provide a signal for the sign of an accommodative response. In the absence of chromatic aberration, there is some evidence that spherical aberration or astigmatism can serve to sign accommodation. The evidence that changes in the Stiles–Crawford effect with defocus provide a signed error signal is equivocal (Kruger, Stark, & Nguyen, 2004).

1.2. Accommodation and perception of absolute distance

Several people have enquired whether the state of accommodation of the eyes can be used to judge the absolute distance of an object. Although Descartes (1664) had no clear idea about the mechanism of accommodation, he proposed that the act of accommodation aids in the perception of depth. Berkeley (1709) made the same suggestion. Wundt (1862) asked subjects to judge whether a black silk thread seen monocularly through a tube was at the same distance in two successive exposures. Subjects could not judge the absolute distance of the thread but could detect a change in depth of about 8 cm at a distance of 100 cm. Hillebrand (1894) used the edge of a black card seen monocularly against an illuminated background so as to remove the depth cue of changing image size. When the stimulus moved abruptly, subjects could detect a change in depth of between 1 and 2 dioptres. Dixon (1895) and Baird (1903) produced similar results. This evidence suggests that people cannot judge the distance of an object on the basis of accommodation but can use changes in accommodation to detect a change in distance. However, more recent experiments have revealed that people have some capacity to judge absolute distance using accommodation.

Swenson (1932) asked subjects to move an unseen marker to the perceived distance of a single binocularly viewed luminous disc at distances of 25, 30, and 40 cm with angular size held constant. Errors were less than 1 cm in the range 25–40 cm. When accommodation was optically adjusted to one distance, and vergence to another distance, judgments of distance were a compromise between the two but with more weight given to vergence. These results indicate only that accommodation contributes to perceived absolute distance. They do not provide a quantitative measure of the contribution of accommodation to judgments of distance.

Fisher and Ciuffreda (1988) asked subjects to point with a hidden hand to monocular high-contrast targets at different distances, with all cues to distance other than accommodation eliminated. As the distance of the target decreased, its apparent distance decreased linearly with increasing accommodation, but there were large individual differences. Subjects tended to overestimate distances that were less than about 3.2 dioptres (31 cm) and underestimate larger distances. Each dioptre change in accommodation induced about a 0.25-dioptre change in apparent distance. With targets with physically blurred edges, perceived distance did not vary with accommodation. Using a similar procedure, Mon-Williams and Tresilian (1999) found that four of six subjects showed a correlation between pointing distance and target distance, but responses were very variable.

1.3. Dynamic accommodation and perception of relative depth

The act of changing accommodation between two objects at different distances might provide information about relative distance. Helmholtz (1909, Vol. 3, p.