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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.

294) found that an illuminated slit with a red filter appeared nearer than a slit with a blue filter. He explained the effect in terms of the change in accommodation required to bring one and then the other slit into focus. Mon-Williams and Tresilian (2000) asked subjects to point with their unseen hand to visual targets at various accommodation distances of 0.5 m or less. Although subjects could not judge the absolute distance of the targets, there was some indication that they could judge whether a target was nearer or farther away than the previous one.

1.4. Object blur and perception of relative depth

An object, such as a poorly focused photograph, may be physically blurred. Unlike defocus blur of the retinal image, physical blur cannot be removed by accommodation. Hence, it is open-loop blur. Artists create an impression of depth by simulating the out-of-focus appearance of objects. Photographers create an impression of depth by using a large aperture to reduce the depth of focus of the lens so that the image of the object of interest is in focus, leaving the surroundings with various degrees of blur. Pentland (1987) discussed the use of gradients of blur in computer vision systems.

Mather (1996) and Marshall, Burbeck, Ariely, Rolland, and Martin (1996) found that a physically sharp textured region with a sharp edge appeared nearer than a coplanar surrounding blurred textured region. However, a sharp textured region with a blurred edge appeared more distant than a blurred surround. O'Shea, Govan, and Sekuler (1997) varied relative blur and relative contrast independently in the two halves of textured bipartite displays. A more blurred region appeared more distant than a less blurred region when contrast was the same. A region of higher contrast appeared nearer than a region of lower contrast when blur was the same. The effects of the two cues were additive over a moderate range of contrast.

1.5. Defocus blur and perception of relative depth

Grant (1942) asked subjects to set a luminous disc to the same distance as an another disc, when cues to distance other than image blur were removed. The standard error of settings was about 0.94 cm at a distance of 50 cm, and 0.8 cm at a distance of 25 cm.

Wilson, Decker, and Roorda (2002) found that subjects could distinguish between the image of a point of light that was nearer than the plane of focus and that of a point beyond the plane of focus. The stimulus was presented for periods of 100 ms after a 2-min training period in which subjects were given knowledge of results. Performance improved with increasing image blur and as pupil diameter was increased from 1 mm to 5 mm.

The first part of our experiment was designed to investigate whether subjects can use defocus blur in the presence of chromatic aberration to judge the depth order of two edges in the absence of error feedback and of all other depth information. First, we asked whether changing blur plus changing accommodation is more effective as a depth cue than stationary blur and fixed accommodation. In one condition, subjects judged the relative depth of two edges when allowed to change accommodation between them. In a second condition, subjects remained fixated on one edge while the other edge was displaced in depth. Secondly, we asked whether subjects can detect the depth order of stimuli exposed for only 210 ms, which is less than accommodation latency. We found that the ability to detect depth order was severely degraded with short exposure. This could have been due to a general loss of sensitivity to blur or to a specific loss of sign information. To decide between these possibilities we measured the threshold for blur detection with brief exposure. If subjects can detect blur but not depth order it reveals that there is a specific loss of sign information.

In the second part of our experiment we asked whether subjects can judge depth order using defocus blur in the absence of chromatic aberration as a cue to the sign of blur. We repeated the same conditions that had been used with tungsten light.

2. Methods

2.1. Apparatus

Fig. 1 shows a plan view of the apparatus. A 2-m long optical bench supported two vertical blackened steel blades at a viewing distance of 37 cm and separated laterally by a 4 mm gap. The vertical inner edges of the blades constituted the test edges. The upper and lower edges of the gap were formed by two horizontal blades 6.5 cm apart. The vertical gap subtended 0.6° in width and 3.4° in height, as shown in Fig. 1. The gap was illuminated by light transmitted by a sheet of opal glass on the front of a box containing the light source at the end of the optical bench. A second optical bench, at right angles to the first, contained similar blades forming a similar gap illuminated in the same way. The vertical inner edges of this second pair of blades were the prefixation edges. The test edges were optically superimposed on the prefixation edges by a beam splitter. There were no other sources of light and the apparatus was lined with black cloth. A computer-controlled electronic shutter (Uniblitz, Model VS14S1TO) was placed on each optical bench just beyond the beam splitter. The prefixation edges and the test edges could be interchanged rapidly by alternating the shutters. The right test edge was mounted on a carriage that could be moved along the

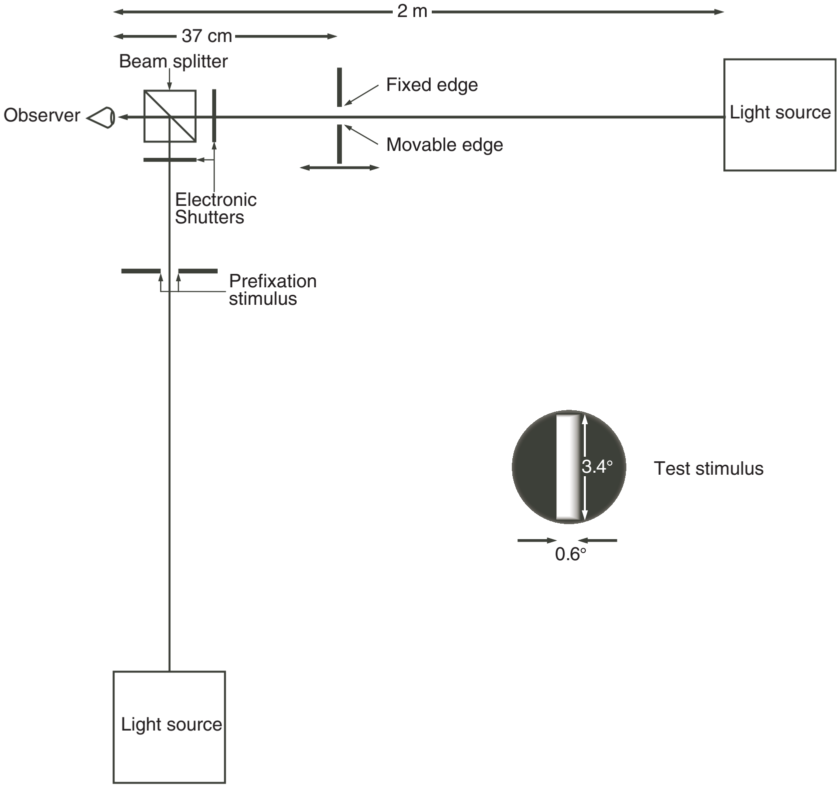

Fig. 1. Plan view of the apparatus not drawn to scale. The inset shows the visual display. The blur of the right edge simulates defocus blur of that edge relative to the in-focus left edge.

optical bench by a stepper motor. A second stepper motor moved the right edge laterally so as to vary the width of the gap. The shutters and motors were controlled by a 486DX computer.

The light source for the prefixation stimulus was a tungsten filament lamp and that for the test stimuli was either a tungsten filament lamp or a monochromatic sodium lamp. The luminance of both gaps under tungsten light was 30 cd/m^2. The luminance of the black surround was too low to be measured. Thus, the edges had a luminance contrast of, or close to, 100%. Since the only light was that coming through the gap, the pupils were nearly fully dilated. A flash photograph of the eye of one subject showed a pupil of diameter 6 mm. We did not apply an artificial pupil because a large pupil gives the smallest depth of field and therefore the highest sensitivity to defocus blur.

2.2. Procedures

The subject adapted to the darkened room for approximately 3 min. The subject's left eye was patched and the head fixed by a bite bar. The bite bar was mounted on a support separated from the table supporting the optical benches, so that the subject could not detect vibrations produced by the stepper motors. The bite bar was adjusted laterally until the subject, viewing with the right eye, detected no lateral motion of the right test edge as it was moved in depth. This ensured that the edge moved along a line of sight and that the width of the gap remained visually constant. However, any displacement of the eye from the correct position would cause the width of the gap to vary as the right edge moved in depth. As an extra precaution against the subject using a change in gap width as a cue to the relative distance of the test edges, the second stepping motor moved the right test edge to a random lateral position between each stimulus presentation. The total amplitude of these random movements was ±5% of the width of the gap. In optometers, changes in image size are usually prevented by viewing stimuli through a Badal lens. A Badal lens was not needed for our stimuli because image size did not change with distance.

The sequence of stimuli was as follows. The coplanar prefixation edges were exposed for 2 s while the subject monocularly focused on and fixated the right edge. After a 100 ms dark interval the test stimulus was exposed under each of the following three conditions. (1) Long exposure time with changing accommodation. The subject looked back and forth between the left and right edges several times and focused well on each edge before responding. (2) Long exposure time with maintained fixation. The subject fixated on a small white spot on the stationary left test edge until a response was made. In both long-exposure conditions, subjects took as long as they wished to respond. (3) Exposure time of 210 ms. This was too short a time for the initiation of an accommodative response. In all three exposure conditions subjects pressed one of two keys to indicate whether the right test edge was nearer than or more distant than the stationary left edge.

In the short-exposure condition, subjects also detected image blur without regard for depth order. For this purpose, a coplanar pair of test edges and a non-coplanar pair of test edges were presented sequentially in random order. Subjects pressed one of two keys to indicate which of the two displays contained edges that differed in blur.

The method of constant stimuli was used in all conditions. The test stimulus was presented 20 times at each of the 13 locations. The locations were drawn randomly from the pool of 13 locations without replacement. The whole procedure was repeated 5 times in one session and there were four sessions for each exposure condition. Each session lasted approximately 45 min. Typically, it took several days to complete the experiment and total observation time was about 24 h. All conditions were performed first with the test stimulus illuminated with tungsten light, which produces longitudinal chromatic aberration. We used tungsten light because, apart from sunlight, it is the most frequent type of polychromatic light. The procedures were repeated when the stimulus was illuminated by monochromatic light of 589 nm from a sodium lamp, which does not produce chromatic aberration.

The time taken to move the right edge between presentations varied with the distance moved. To prevent the subject using the time interval or the sound of the stepping motor as cues to the distance moved, the right test edge was first moved to a random location before it was finally moved into the test location. Noise from the stepping motors was effectively masked by recorded music played in the room.

Detection thresholds were obtained by fitting Weibul functions to the pooled data. Parameter estimation was done using Solver Function in Microsoft Excel (1985–2001 Microsoft Corporation). The Solver was set to obtain best fit by minimizing the sum of squared errors. The threshold was obtained at 80% correct detection level.

2.3. Subjects

Initially we tested five subjects. However, we report results for only the three subjects (AT, KK, VN) who could perform above chance when allowed long exposure under tungsten illumination. None of the subjects had eye defects except for the need for optical corrections. Their ages ranged from 19 to 37 years. They all had visual acuity of 6/6 or better. The experiments were conducted with the understanding and written consent of each subject. Subjects were paid for their participation. Table 1 shows visual data for each of the subjects.

Table 1
Visual data for each subject (right eye only)

Subject	Age (years)	Snellen acuity	Optical correction	Near focus (cm)
AH	20	6/6 N5	CL −6.0	10
AT	20	6/6 N5	Sp −3.75/−0.25*0.5°	11
KK	33	6/6 N5	No correction	10
SY	19	6/6 N5	Sp −1.25	12
VN	37	6/6 N5	Sp −4.75/−0.5*12°	15

Subjects wore their own optical corrections that were either spectacles (Sp) or contact lenses (CL). Near focus was assessed by bringing N5 size letters towards the subject's right eye and asking the subject to report when the letters first appeared blurred.

3. Results

Fig. 2 shows the results for each of the three subjects when the test stimulus was illuminated by tungsten light for as long as it took subjects to respond. Under these conditions, all three subjects could detect the depth order of the test edges when their separation reached a threshold level. The mean depth-discrimination threshold was 0.31 D when subjects looked back and forth between the test edges and was 0.25 D when they fixated the stationary left edge. A two-factor ANOVA revealed that the 'near' thresholds are not significantly different from the 'far' thresholds.

Fig. 3 shows the results for each of the three subjects when the test stimulus was illuminated by tungsten light for only 210 ms. In this condition, only one of the three subjects could detect the depth order of the stimuli. The other two subjects tended to make 'near' default judgments for small depth intervals and 'far' default judgments for large depth intervals. The averages of the 'near' and 'far' responses of these two subjects remained close to the level of chance performance, as shown by the dashed line in Fig. 3a. Wilson et al. (2002) found that all their eight subjects could distinguish between the blur of a near point and that of a far point when the stimulus was presented for only 100 ms. However, their subjects were provided with error feedback.

With short exposure, all our subjects could detect the blur of the image of the right test edge when the separation between the edges reached a threshold value. The mean blur-detection threshold was 0.32 D when the right edge was near and 0.52 D when the right edge was far. A two-factor ANOVA revealed that this difference was significant at the 0.05 level. The overall mean blur-detection threshold was 0.45 D. Thus, with a short stimulus duration, all subjects could detect the blur of the image of the out-of-focus edge but only one subject could detect the depth order of the edges.

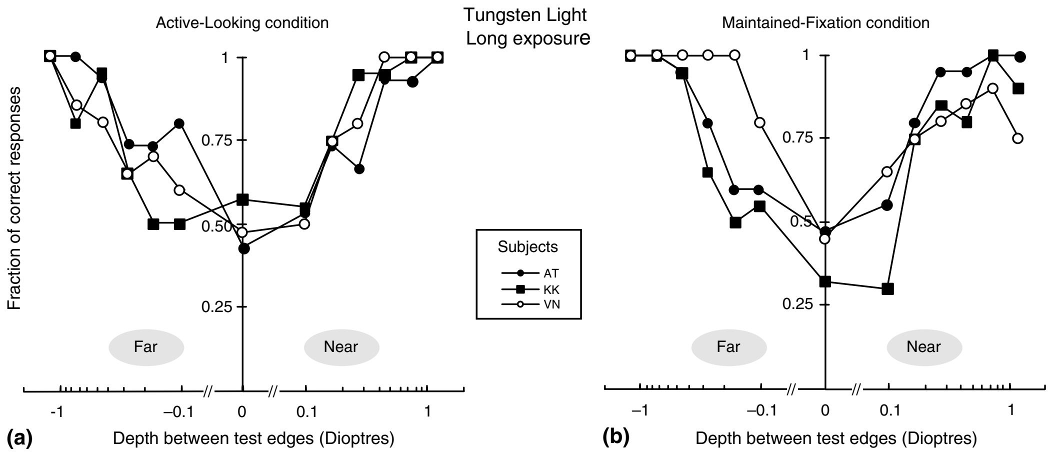

Fig. 2. Detection of the depth order of test edges illuminated for an extended period with tungsten light. (a) Results for the active-looking condition in which subjects looked back and forth between the test edges. (b) Results for the maintained-fixation condition in which subjects maintained fixation on the left edge.

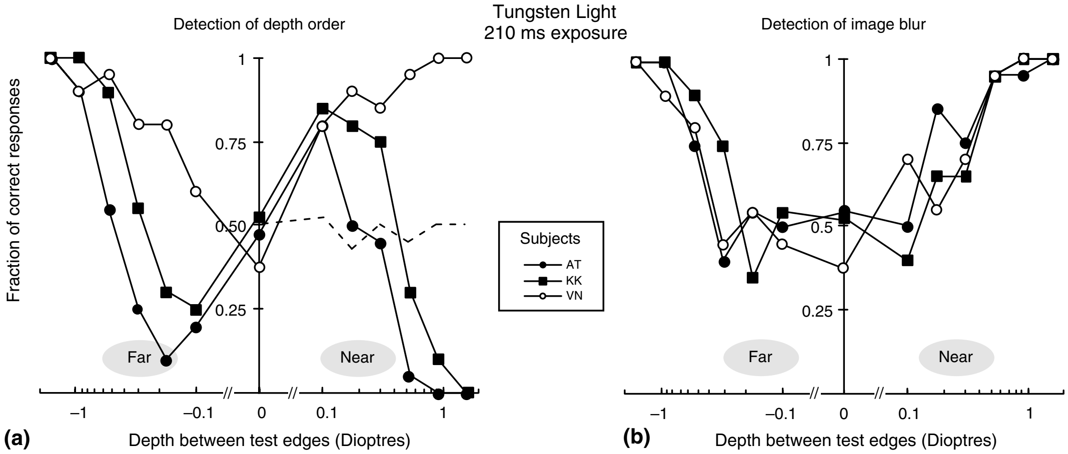

Fig. 3. Results for test edges illuminated by tungsten light for 210ms. (a) Detection of depth order. The dashed line gives pooled 'far' and 'near' responses of subjects AT and KK. (b) Detection of unsigned image blur.

Fig. 4 shows the results when the test stimulus was illuminated by sodium light for as long as it took for subjects to respond. With active looking between the test edges, one subject could detect the depth order of the test edges, although with a large threshold of 0.67D. The judgments of the other two subjects became erratic at larger depth separations. When subjects remained fixated on the stationary left edge, none of them could, reliably, detect the depth order of the edges. The dashed line in Fig. 4b shows that the average of the 'near' and 'far' responses remained close to the level of chance performance. Thus, with monochromatic light, there was some evidence of discrimination of depth order but only when subjects were allowed to look between the edges.

Fig. 5 shows the results for monochromatic light and an exposure duration of 210ms. Only one subject could reliably detect the depth order of the edges. The other two subjects made default judgments to 'near' for small depths and to 'far' for large depths. The dashed line in Fig. 5a shows that the average of the 'near' and 'far' responses remained close to the level of chance performance. However, Fig. 5b shows that all three subjects could reliably detect image blur with a mean threshold of 0.49D. The mean blur-detection threshold was 0.32D when the right edge was near and 0.63D when the right edge was far. A two-factor ANOVA revealed that this difference was significant at the 0.05 level. Table 2 shows threshold values for all conditions for the three subjects who could perform the task.

4. Discussion

The principal conclusion from our experiments is that, with tungsten light, some people are able to judge the relative depth order of two edges when the only

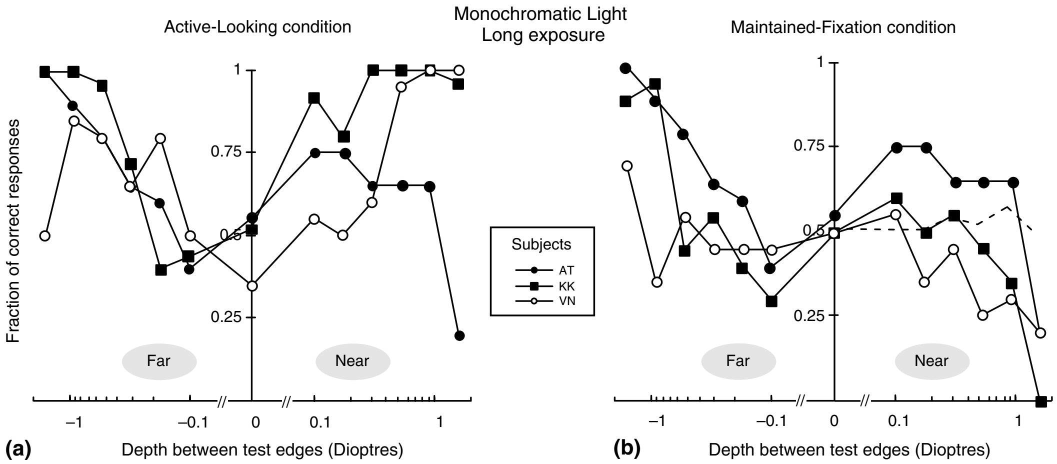

Fig. 4. Detection of the depth order of test edges illuminated for an extended period with tungsten light. (a) Results for the active-looking condition. (b) Results for the maintained-fixation condition. The dashed line gives the pooled 'far' and 'near' responses, averaged over three subjects.

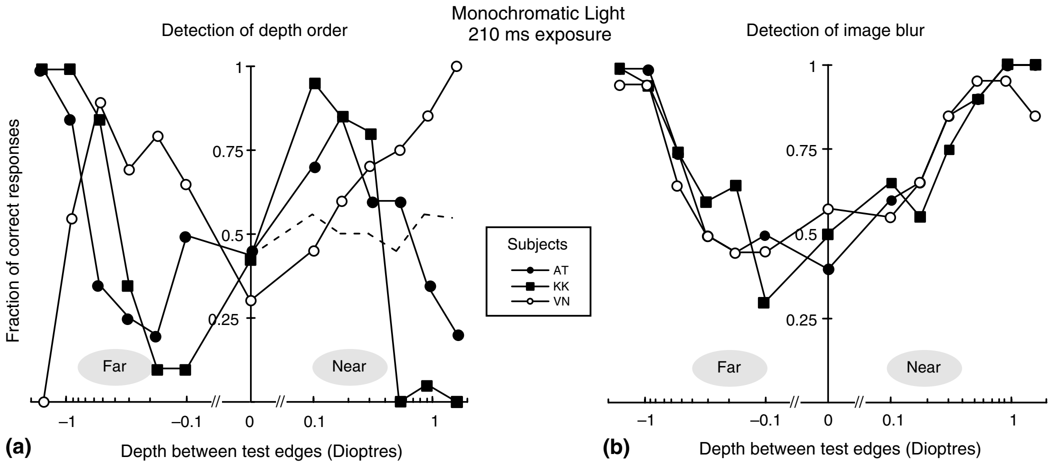

Fig. 5. Results for test edges illuminated by monochromatic light for 210 ms. (a) Detection of depth order. The dashed line gives pooled 'far' and 'near' responses. (b) Detection of unsigned image blur.

Table 2
The table shows the mean detection thresholds for each condition

Test condition	Tungsten light				Sodium lamp			
	Long exposure depth detection		Short exposure		Long exposure depth detection		Short exposure	
	Active looking	Maintained fixation	Depth detection	Blur detection	Active looking	Maintained fixation	Depth detection	Blur detection
Near threshold	0.24 D	0.25 D	–	0.32 D	–	–	–	0.32 D
Far threshold	0.38 D	0.24 D	–	0.52 D	–	–	–	0.63 D
Mean threshold	0.31 D	0.25 D	–	0.45 D	–	–	–	0.49 D

Each value is the mean for three subjects in dioptres. Dashes indicate that the threshold was not obtainable.

information is provided by relative blur of the retinal images. Two of the five subjects we tested did not perform above chance in the most favourable conditions. Other investigators have reported that subjects differ widely in their accommodative responses in the presence or absence of chromatic aberration (Campbell & Westheimer, 1959; Fincham, 1951; Stark et al., 2002).

The other three subjects performed well with tungsten light. They performed as well when they looked from one edge to the other several times as when they remained focused on one edge. If they had performed well only when looking between the edges we would have concluded that they were relying on signals associated with large changes in accommodation. These signals could be dynamic changes in image blur or afferent signals to the ciliary muscles. But even if our subjects used such signals when allowed to change accommodation, they could not have used them when they remained fixated on one of the edges. We conclude that, in this condition, depth judgments were based on the sign of image blur.

The second conclusion is that, with tungsten light, the ability to use image blur to detect the depth order of two edges is severely degraded when the stimulus is presented for only 210 ms. Only one of our three subjects could detect depth order with a 210 ms stimulus. Since all three subjects could detect differences in image blur with brief exposure, we conclude that there was no general loss of blur sensitivity but rather a specific loss in the ability to detect the sign of blur. The mean blur-detection threshold for the three subjects with brief exposure was 0.45 D. This is similar to the threshold of 0.44 D reported by Campbell (1957) but larger than the threshold of 0.18 D reported by Jacobs, Smith, and Chan (1989) or of 0.11 D reported by Rosenfield and Abraham-Cohen (1999). However, in these previous studies, subjects were allowed to look as long as they wished, while we had an exposure of only 210 ms.

Two of our subjects may have failed to detect depth order with short exposure because they depended on changes in accommodation, which cannot occur with brief exposure. But if so, they would have been able to use the effects of changing accommodation with monochromatic light with long exposure. In fact, under monochromatic light, only one subject could judge depth order when allowed to change accommodation and none of the subjects could perform with long exposure and maintained fixation. We conclude that subjects require more time to detect the sign of blur than to detect blur. Further experiments are needed to reveal how much time is required to detect the sign of blur, both for controlling the sign of accommodation and for the detection of depth order.

The third conclusion is that the ability to detect the depth order of two edges is severely degraded when the stimulus is illuminated by monochromatic light, which lacks the chromatic aberration cue to relative depth. Other investigators have shown that accommodative responses are degraded in monochromatic light. There was some evidence of depth-order discrimination, especially in one subject, when subjects were allowed to look from one edge to the other under monochromatic light. We suggest that, in this condition, subjects used trial-and-error hunting to achieve some success with monochromatic light. After a few changes in accommodation with a given stimulus, they would discover which way to accommodate to bring each edge into focus. They could then base their judgments of relative distance on efferent signals associated with changing accommodation. In monochromatic light, depth-order discrimination was absent in all subjects when they remained fixated on one edge. The hunting strategy could not be used in this condition. Subjects could perhaps have used signals associated with spontaneous fluctuations of accommodation, but their performance revealed that they did not do so. All subjects could detect blur in an edge illuminated by monochromatic light for only 210 ms. With brief exposure, the mean blur-detection threshold for monochromatic light was similar to that for tungsten light. Thus, monochromatic light provides adequate illumination for blur detection but provides little or no information about the sign of relative depth when accommodative hunting is not possible.

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