Perception, 1981, volume 10, pages 53-62

Is accommodation colorblind? Focusing chromatic contours

Jeremy M Wolfe
Massachusetts Institute of Technology, Department of Psychology, 79 Amherst Street, Cambridge, Massachusetts 02139, USA
D Alfred Owens
Franklin and Marshall College, Department of Psychology, Lancaster, Pennsylvania 17604, USA
Received 27 May 1980, in revised form 29 August 1980

Abstract. Two adjacent regions define an edge if they differ in either color or luminance. If the difference is purely chromatic, the edge is said to be isoluminant. Isoluminant contours are often perceptually unstable. Perhaps some of this instability could be explained if isoluminant contours were difficult to bring into focus. To test this hypothesis, a vernier optometer was used to measure the accuracy of steady-state accommodation for the vertical boundary of a red-green bipartite field. This edge was presented at optical distances of 0, 1·5, 3·0, and 4·5 diopters, with brightness contrasts between the two hemifields of 0% (isoluminant), 15%, 58%, and 100%. Accommodation was essentially unresponsive to the isoluminant edge and exhibited increasing focusing accuracy with increased brightness contrast. Control experiments replicated this finding for red-orange, green-blue, and white-white fields. These results imply that luminance contrast is a necessary stimulus for monocular accommodation. Inappropriate accommodation may be a factor contributing to the perceptual instability of isoluminant patterns.

1 Introduction

For a human observer two adjacent regions can define a contour only if they differ in either luminance or color. Most real-world contours differ in both. If all luminance information is removed, a purely chromatic or 'isoluminant' contour results. Such stimuli pose unexpected problems for the visual system. Leibmann (1926) noted that isoluminant figures seemed strangely unstable. The absolute location of borders was hard to determine and the figure seemed to fade when viewed for any length of time. Koffka and Harrower (1931) refer to the 'poor organizing ability' of isoluminant figures. More recently, Gregory (1977) has noted the disruptive effects of isoluminance on perceptual tasks ranging from face recognition to reading. These effects cannot be explained entirely as a loss in acuity for isoluminant targets. In fact, Cavonius and Schumacher (1966) showed that grating acuity for red-green isoluminant targets was normal (equivalent to 20/20 Snellen acuity). Further, Gregory (1977) concluded that the 'breakup of complex patterns' was probably not to be attributed to an acuity loss.

Since the efforts of the Gestalt psychologists (Leibmann 1926; Koffka and Harrower 1931), few theories have been put forward to account for the disruption of spatial vision under isoluminant conditions. Gregory (1977) and Lu and Fender (1972) suggest that certain aspects of form perception depend primarily on luminance information. Boynton (1978), in his study of minimally distinct borders, argues that at equal luminance the distinctness of a border is a function of the ratio of red to green cone excitation and that borders will be most prone to fading when excitation is equalized at the tritanopic confusion points—points where pairs of colors would appear identical to the tritanope but not to the normal observer.

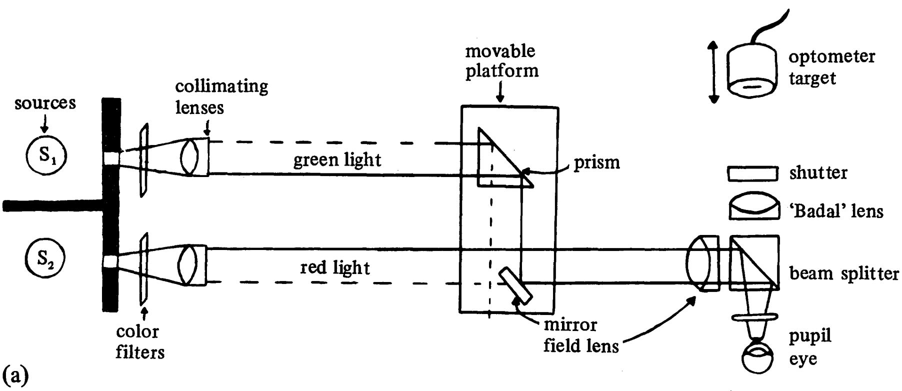
It is possible that a factor even more peripheral than the receptors contributes to some isoluminant effects. Pattern perception is dependent on retinal image quality, and the quality of the image, in turn, depends on the ability of the observer to focus accurately. It now appears that observers are incapable of accurately accommodating to isoluminant contours. The unsuccessful attempts of the accommodative system to focus such contours could lead to some of the apparent instability of isoluminant figures.

2 General method

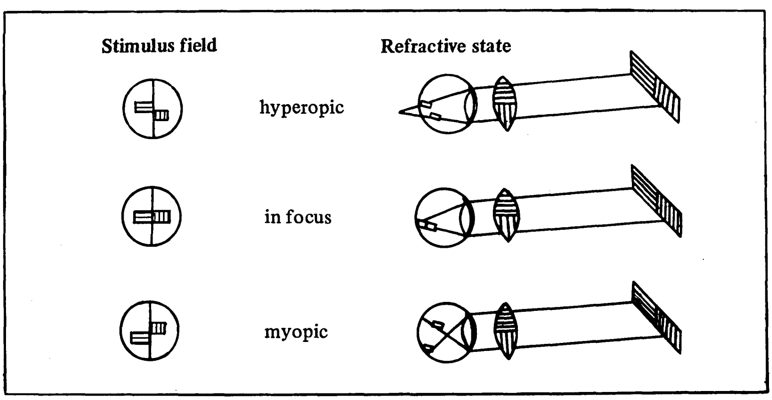
2.1 *Apparatus*

The accommodative state of the subjects was measured while they viewed a 5·4 deg of arc bipartite field. The apparatus is illustrated schematically in figure 1a. Two beams of collimated light were combined so that the left half of one beam and the right half of the other were viewed by the subject through Maxwellian view optics. This was done by having a first-surface mirror reflect half of one beam while blocking half of the other beam. With proper alignment of the optical system and of the subject, no brightness difference existed at the edge between the two hemifields. Luminance could be independently varied in each field. To eliminate any sharp contour at the outer edges of the stimulus, field stops were placed at an optical distance of 10·9 diopters in each channel. Hence, the field appeared to fade gradually into darkness at its outside border.

With white light, the field luminance was set to approximately 5·0 cd m^{-2}. All color fields were brightness-matched to this standard (see section 2.2). Colored hemifields were produced by inserting celluloid filters into the collimated light paths.



(a)



(b)

Figure 1. (a) Schematic drawing of the apparatus used to produce a bipartite field, and of the vernier optometer used to measure steady-state accommodation. The luminance of each half of the bipartite field could be independently varied. (b) Illustration of vernier optometer function (see text for details).

The following Edmund Scientific filters were used: 817–orange, passing wavelengths primarily between 600 and 700 nm; 823–red, peaking at 700 nm and passing little below 650 nm; 856–blue, having a roughly symmetrical peak about 465 nm; and 874–green, roughly symmetrical about 525 nm. In the experiments four color pairs were used: red–green, red–orange, blue–green, and white–white.

The purpose of this investigation was to examine accommodation under conditions of subjective isoluminance. This state was psychophysically defined for each subject by having the subject adjust the brightness of one half of the bipartite field until it matched the other half. Thus, the subjective isoluminant point is, in fact, an isobrightness point. For each subject the point will differ from photometric isoluminance by a small and unique constant (Gregory 1977). Though, as Gregory points out, these individual differences may prove interesting, the term isoluminant will be used here to refer to the subjective point described above. It is worth noting that, within the accuracy of our apparatus, subjects found the point of subjective brightness match to be identical to the minimally distinct border (Boynton 1978) when informal comparisons were made.

After an isoluminant match was made, contrast was varied by inserting calibrated Kodak Wratten neutral-density filters into one of the two channels. The 0% contrast point was defined as the isoluminant condition. Contrasts relative to this zero point were computed as:

$$\frac{L_{max} - L_{min}}{L_{max}} = 100 - T,$$

where L is luminance, and T is percent transmission of the neutral-density filter. 100% contrast was produced by extinguishing the light in one channel. Since the isoluminant point as defined here differs by a small amount from the photometric isoluminant point, luminance contrast, as defined here, will differ by a small amount from true luminance contrast. As will be seen, neither the absolute luminance contrast nor the spectral composition of the stimuli are central to the conclusions of this paper. Thus, while the use of subjective brightness matches leads to the use of slightly different sets of stimuli for different subjects, it is important to realize that any variation in the stimuli will tend to obscure and not artificially enhance the results.

Accommodation was measured with a vernier optometer that takes advantage of the Scheiner principle (Moses 1971; Simonelli 1979). The subject was required to judge the alignment of two adjacent luminous line segments that were flashed briefly (200 ms) on the stimulus field. The optometer stimulus was constructed by illuminating a small horizontal slit from behind. Two Polaroid filters were positioned in front of the slit so that the left and right halves of the slit emitted light polarized along orthogonal axes. All stimuli were viewed through an artificial pupil, 3·5 mm in diameter, which also contained two orthogonal Polaroid filters, one over the top half and one over the bottom half of the pupil. Thus, the left half of the optometer target was imaged only through the upper half of the ocular optics, and the right half of the optometer target was imaged only through the lower half of the ocular optics.

With this arrangement, the two halves of the optometer target appeared in horizontal alignment only when the optometer slit and the retina were at conjugate foci. As illustrated in figure 1b, when the optometer target is nearer than the eye's focus (hyperopic), the line segment imaged by the upper portion of the ocular optics appears to be above that imaged by the lower portion of the ocular optics. Conversely, when the optometer target is farther than the eye's focus (myopic), the portion imaged through the upper half of the ocular optics appears below that imaged through the lower half.

The optical distance of the optometer target was varied according to the 'Badal principle' by a field lens positioned in the light path of the optometer one focal length from the artificial pupil (Ogle 1967). This simple optical system provided two advantages:
(a) the optical distance of the optometer target could be varied from $-2 \cdot 0$ diopters, 'beyond' optical infinity (hyperopia), to $+4 \cdot 5$ diopters, the focal length of the field lens;
(b) this variation could be accomplished over a short section of optical bench with no change in the angular subtense of the optometer target (0·3 deg x 1·4 deg).

Exposure of the optometer target was limited to 200 ms by a mechanical shutter, and the target was superimposed on the bipartite field by a beamsplitter.

2.2 *Procedure*
As described in section 2.1, isoluminance was psychophysically defined as the point where the two halves of the stimulus field appeared equally bright. Using the method of adjustment, subjects made these brightness matches for the red–green, red–orange, blue–green, and white–white hemifield pairs.

In all experiments subjects maintained head alignment with the aid of a chinrest. Subjects were asked to align themselves in such a way as to minimize any brightness artifacts at the border between the hemifields. On each trial the vertical edge of the bipartite field was set to one of the four optical distances: 0·0, 1·5, 3·0, or 4·5 diopters. The subject then began viewing the stimulus. The optometer target was flashed for 200 ms and the subject reported the presence and direction of any apparent vernier offset. By a method of successive approximation the optical distance of the optometer target was varied over several presentations until the subject reported that no vernier offset could be seen. The optical distance of the optometer target was then taken as the measure of the accommodative state of the subject. In all experiments three measurements were taken for each optical distance of the bipartite stimulus.

3 Experiment 1. Red–green borders
3.1 *Method*
In this experiment the left half of the bipartite field was red and the right green. Contrast was varied from 100% (red–black) through 0% (red–green, isoluminant) to 100% (black–green) (see section 2.1). Seven levels of contrast were tested: 100%, 58%, 15%, 0%, 15%, 58%, and 100%; duplicate contrast values represent red-brighter and green-brighter conditions. As described above, all contrasts are relative to the psychophysical isoluminant point which was defined as 0%. To establish a baseline level of accommodative accuracy, subjects were also tested with a high-contrast matrix of Snellen 'E's as the accommodative stimulus. The 'E's subtended 1·7 deg visual angle with a stroke width of 20·3 min. Accommodative responses to such targets are usually as good as any the subject can produce.

To normalize the results all other measures of accommodative response are stated as percentages of this presumed maximum. For reasons as yet unknown, in experiments of this sort the magnitude of monocular accommodative response varies widely from subject to subject, whilst the pattern of results is remarkably consistent from subject to subject. That is, a poor accommodative stimulus for one subject will be a poor stimulus for other subjects, though the magnitude of the response to that stimulus will not be the same for all subjects. Normalizing the data on the responses of an individual subject to Snellen 'E's eliminates the differences in magnitude and allows meaningful comparisons to be made between subjects.

Four subjects were tested. Two knew the purpose of the experiment and were experienced observers. One was naive as to the purpose of the experiment, though she was experienced with measures of accommodation. The fourth was naive and inexperienced.

Stimulus contrast was randomly varied. Within a contrast level, stimulus distance was randomly varied. For each subject the three responses made to each stimulus–distance combination were averaged. Accommodative responsiveness was evaluated in terms of the slope of the function relating accommodative responses to the distance of the fixated stimulus. If the subject focused accurately for all distances, the slope of the accommodative response function would be unity. If the subject was unable to accommodate for the target stimulus, accommodative responses would tend to shift toward the subject's characteristic 'resting state' or 'dark focus' of accommodation (Leibowitz and Owens 1975; 1978) resulting in a zero slope. Intermediate slopes reflect intermediate accommodative function. As previously noted, to normalize the results from the four subjects accommodative responsiveness was expressed as a percentage of the slope obtained for the Snellen 'E's.

3.2 *Results*

Raw data, in the form of accommodative response functions for a single subject (JMW), are illustrated in figure 2. Separate functions represent the focusing performance obtained with Snellen 'E's and with the red–green vertical edge at three contrasts: 100% (red–black), 58%, and 0% (isoluminant). As reflected by the slopes of these functions, accommodative responses were most accurate for the Snellen 'E's (slope = 0·79). Accommodation was virtually identical for the red–black edge (slope = 0·77) and showed progressively diminished accuracy as the brightness contrast was reduced. The slope for the isoluminant edge (0·15) is only one-fifth that for the high-contrast targets. To normalize these results, the slope of the response function for the 'E's is set to 100%. The 0·77 slope for the red–black edge is thus 97% of the best response, while the response to the isoluminant, red–green edge is only 19%.

Each point is the average of three measures. The range of those measures is never greater than 1 diopter and is usually less than 0·5 diopter. Similar results were obtained from the other three subjects.

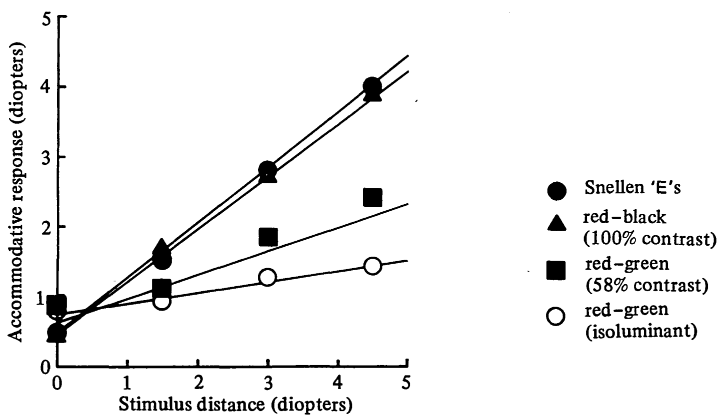


Figure 2. The accommodative response function of subject JMW for four stimuli. The steeper the slope of the function, the more accurately the subject is accommodating. Snellen 'E's and the red–black, high contrast edge stimulate far more accurate accommodative responses than does the isoluminant edge. An edge of intermediate luminance contrast produces intermediate accommodative responses.

For each subject, accommodative responsiveness for brightness contrast of the red–green field is represented as a percentage of the slope obtained with Snellen 'E's. These percentages, averaged for all four subjects, are presented in figure 3. The derived function shows a dramatic loss in the accuracy of accommodation as luminance contrast is reduced. The slope of the accommodative response function for a red–green edge at isoluminance is only 15% of that obtained with Snellen 'E's, and is only 20% of that obtained with high-contrast red–black or green–black edges. All four subjects show very similar patterns of results. Within a contrast level, normalized results may vary by as much as 25% between subjects. However, there is no overlap between the normalized results for ±100% and ±58%, or between the results for ±58% and ±15%. The results for +15%, 0%, and −15% do overlap. Apparently chromatic contrast alone is not an effective stimulus for accommodation.

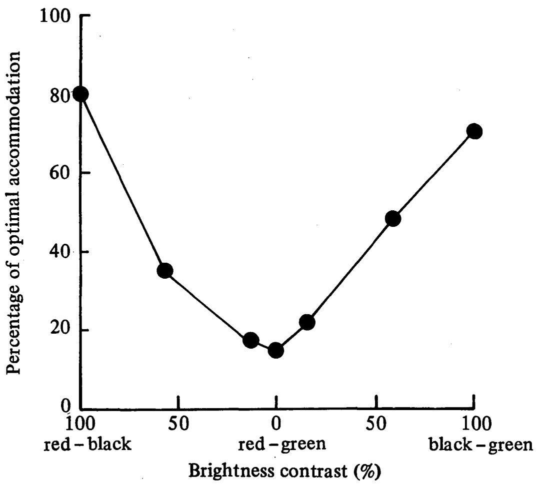


Figure 3. Accommodative response as a function of stimulus luminance contrast for red–green bipartite fields. The accommodative response is computed as a percentage of the response to the high-contrast Snellen 'E' target (see text). Accommodative response is weakest at isoluminance. (Average for four subjects.)

4 Experiment 2. Comparison of chromatic and achromatic contours

4.1 *Method*

The results of experiment 1 imply that chromatic contrast makes little or no contribution to the control of steady-state accommodation. Thus, a red–green stimulus should produce no greater accommodative response than an achromatic stimulus of the same contrast. To test this hypothesis three sets of stimuli were compared:

(i) red–black to red–green (isoluminant),
(ii) black–green to red–green (isoluminant),
(iii) black–white to white–white (isoluminant and isochromatic).

The first two series were the same as the two 'arms' of the function shown in figure 3. In the third series, luminance information was the same as that in (i) and (ii) but chromatic contrast was absent. Thus, the white–white condition was isochromatic as well as being isoluminant.

Two subjects were tested with the achromatic series. As with the red–green stimuli, brightness contrasts of 100%, 58%, 15%, and 0% were used. At isoluminance the brightnesses of the red, green, and white fields were equated by simultaneous brightness matches made by both subjects. All other aspects of the experiment were identical to those in experiment 1.

4.2 *Results*

Figure 4 shows the average results of two subjects for the three stimulus series. Again accommodative responsiveness is represented as a percentage of the slope obtained with Snellen 'E's. No significant difference exists between the results for the chromatic edge and those for the achromatic edge. Only at 0% brightness contrast are the responses to the chromatic contours slightly better than those to achromatic contours. The difference is small and not statistically significant. We conclude from experiment 2 that the introduction of strong chromatic contrast at an edge does not improve the responsiveness of the accommodative system.

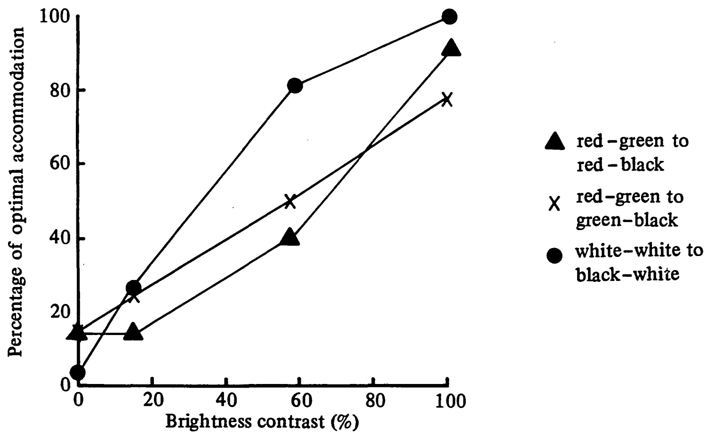


Figure 4. Comparison of accommodative responses to chromatic and achromatic contours of equal contrasts. The addition of color to an edge does not significantly improve accommodation. (Average for two subjects.)

5 Experiment 3. Other color combinations

5.1 *Method*

The effects seen at isoluminance for a red-green contour might have been specific to that color combination. Therefore, two other color combinations were tested at isoluminance: red-orange and blue-green. The luminance of the red and green fields was held at the same level as in experiments 1 and 2, and subjective isoluminant conditions were again obtained by brightness matches. Here orange was matched to red, and blue to green. The two subjects in experiment 2 were also tested in experiment 3.

5.2 *Results*

Figure 5 presents average results for the red-orange and blue-green isoluminant contours along with the red-green and white-white conditions from experiments 1 and 2. For comparison, results are shown for the white-black, red-black, and green-black high-contrast edges. It is clear that the isoluminant effect is not specific to red-green contours. In fact, both red-orange and blue-green produced smaller accommodative responses than red-green. This result is concordant with the finding of Bowen et al (1977) that isoluminant effects (here two-pulse resolution decrements) are greater for colors of similar wavelength. In our experiments blue-green produces the most striking effects. The edge stimulated no accommodative response even in practiced subjects. Koffka and Harrower (1931) studied what they loosely called the 'organizing ability' of colored contours. In picturesque language, they labelled blue and green as 'soft' colors, and red and yellow as 'hard' colors. They reported that soft colors produced more pronounced effects at isoluminance. Our data indicate that their soft colors produce the most profound disruption of accommodation.

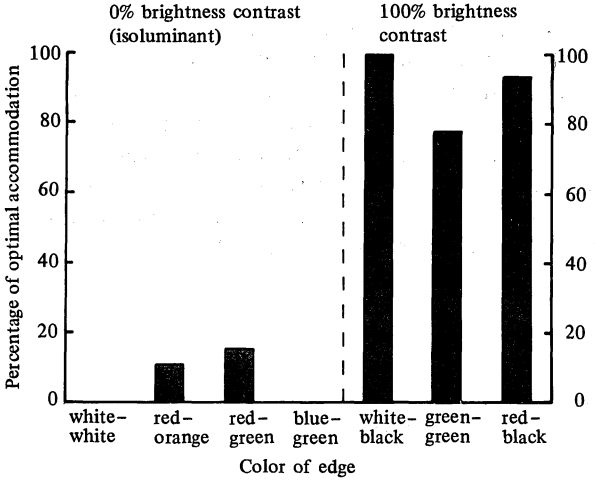


Figure 5. Comparison of accommodative responses to isoluminant edges and high-contrast edges. All isoluminant edges produced significantly smaller accommodative responses than did the high-contrast edges.

6 Discussion

Our results indicate that chromatic contrast in the absence of luminance contrast is not a sufficient stimulus for accurate steady-state accommodation. This finding expands our understanding of the mechanism of accommodation and of the appearance of isoluminant figures.

6.1 *Isoluminance and the mechanism of accommodative control*

Previous experiments have shown that spatial luminance contrast is a sufficient stimulus for monocular accommodation (Owens 1980). On the basis of the present findings, we suggest that it is not only sufficient but also necessary. Owens (1980) demonstrated that the accuracy of accommodation for sinusoidal gratings of various spatial frequencies is highly correlated with the psychophysically measured contrast sensitivity function. While perception and accommodation show similar responses to the spatial distribution of luminance, they are very different in their responses to the spatial distribution of chromaticity. The perceptual system can detect 1 nm differences in the wavelength of two adjacent regions (Laurens and Hamilton 1923). The accommodative system is apparently insensitive to contours formed by widely separated wavelengths equated for brightness. If this interpretation is correct, then theories that attribute accommodative control to the detection of the weak color fringes arising from the chromatic aberration of the eye (eg Fincham 1953) become more difficult to construct.

6.2 *Accommodation and the perception of isoluminant figures*

The failure of the accommodative system to focus accurately isoluminant contours may have a bearing on the perception of such contours. All subjects noticed that the accommodative system continues, without success, to try to focus an isoluminant edge. Although we did not measure accommodation continuously, the intermittent measures taken with the vernier optometer and the subjective impressions indicated that on viewing the isoluminant contours accommodation fluctuated at a relatively slow temporal frequency. Such a fluctuation of accommodation would lead to a continuous change in the retinal image that may account for some of the frequently noted perceptual instability of isoluminant contours. 'Jazziness' (Gregory 1977) and 'poor organizing ability' (Leibmann 1926; Koffka and Harrower 1931) are other terms describing the same basic effect.

A number of specific isoluminant effects may be due, at least in part, to a failure of accommodation. For example, Leibmann (1926) noted that isoluminant effects seemed more profound if the stimulus was far away. This could be due to increased blur created as the stimulus was placed farther away from the subject's resting state of accommodation, a state that corresponds to an intermediate distance for most subjects (Leibowitz and Owens 1975, 1978).

The apparent fading of isoluminant figures may represent a combination of effects described by Krauskopf (1963), Cornsweet (1970), and the present paper. It is well known that a stabilized image fades after a few seconds (Ditchburn and Ginsborg 1952; Riggs et al 1953). Krauskopf found that this effect is more pronounced as the figure approaches isoluminance. Cornsweet produced a demonstration of fading with a nonstabilized image in which a low-spatial-frequency achromatic contour tends to fade with normal fixation. The fading of isoluminant figures can be explained in terms of these findings. Inaccurate accommodation would optically filter high spatial frequencies from the retinal image, resulting in a stimulus similar to Cornsweet's figure. Since isoluminance enhances stabilized image effects, it should also enhance the Cornsweet effect. The result would be a fading of a physically sharp isoluminant contour with fixation. If this formulation is accurate, then isoluminant contours should be less prone to fading if they are placed at the distance of the subject's resting state of accommodation.

Accommodation cannot be invoked as the explanation for all phenomena occurring at isoluminance. In particular, it has been claimed that isoluminant stimuli do not produce figural aftereffects (Hochberg and Triebel 1955), the Delboeuf illusion (Oyama 1962), the McCollough effect (Harris and Barkow 1969), or the oblique effect (Kelly 1975). It is hard to see how any of these deficits can be attributed to accommodative difficulties.

In fact, it is possible that none of the isoluminant effects can be attributed to accommodative difficulties. If the explanation has any power, then the instability of isoluminant figures should be reduced if accommodation is paralyzed or otherwise eliminated as a factor. No formal experiments have examined this hypothesis. One recently presbyopic observer notes, however, that isoluminant figures look as "unstable and indistinct as they always did" (anonymous reviewer, personal communication).

Finally, we wish to acknowledge that this paper is not the first to suggest that isoluminant stimuli might not drive accommodation. In a single note in a very long article Koffka and Harrower (1931) state, without experimental evidence, that isoluminant figures are "liable to be less successful in controlling accommodation". Fifty years later we have confirmed that conjecture.

In summary two conclusions can be drawn from the finding that isoluminant contours do not drive accommodation. First, the accommodative system is insensitive to color contrast. Second, some of the perceptual phenomena seen in isoluminant figures may not be entirely due to the inability of perceptual processes to handle such stimuli, but may be influenced by the inability of accommodation to bring such stimuli into focus and to pass a clear, stable image to the rest of the visual system. Testing the latter conclusion is a matter for further research.

Acknowledgements. The authors thank Julie Sandell and Debbie Owens for technical assistance and Eileen Birch and two anonymous reviewers for useful comments on the manuscript.

References

Bowen R W, Lindsey D T, Smith V C, 1977 "Wavelength effects on temporal resolution" ARVO abstract in *Investigative Opthalmology (Supplement)* **16** 124

Boynton R M, 1978 "Ten years of research with the minimally distinct border" in *Visual Psychophysics and Physiology* Eds J C Armington, J Krauskopf, W Wooten (New York: Academic Press)

Cavonius C R, Schumacher A W, 1966 "Human visual acuity measured with colored test objects" *Science* **152** 1276-1277

Cornsweet T N, 1970 *Visual Perception* (New York: Academic Press)

Ditchburn R W, Ginsborg B L, 1952 "Vision with a stabilized retinal image" *Nature* **170** 36-37

Fincham E F, 1953 "Factors controlling ocular accommodation" *British Medical Bulletin* **9** 18-21

Gregory R L, 1977 "Vision with isoluminant colour contrast: 1. A projection technique and observations" *Perception* **6** 113-119

Harris C S, Barkow B, 1969 "Color/white grids produce weaker orientation specific color after-effects than do color/black grids" *Psychonomic Science* **17** 123

Hochberg J E, Triebel W, 1955 "Figural aftereffects with colored stimuli" *American Journal of Psychology* **68** 133-135

Kelly D H, 1975 "No oblique effect in chromatic pathways" *Journal of the Optical Society of America* **65** 1512-1514

Koffka K, Harrower M R, 1931 "Colour and organization" *Psychologische Forschung* **15** 145-192, 193-275

Krauskopf J, 1963 "Effect of retinal image stabilization on the appearance of heterochromatic targets" *Journal of the Optical Society of America* **53** 741-744

Laurens H, Hamilton W F, 1923 "The sensitivity of the eye to differences in wavelength" *American Journal of Physiology* **65** 547-568

Leibmann S, 1926 "Über das Verhalten farbiger Formen bei Helligkeitsgleichheit von Figur und Grund" *Psychologische Forschung* **9** 300-353

Leibowitz H W, Owens D A, 1975 "Anomalous myopias and the intermediate dark focus of accommodation" *Science* **189** 646-648

Leibowitz H W, Owens D A, 1978 "New evidence for the intermediate position of relaxed accommodation" *Documenta Ophthalmologica* **46** 133-147

Lu C, Fender D H, 1972 "The interaction of color and luminance in stereoscopic vision" *Investigative Ophthalmology* **11** 482-490

Moses R A, 1971 "Vernier optometer" *Journal of the Optical Society of America* **61** 1539

Ogle K N, 1967 "Optics: an introduction for opthalmologists" (Springfield, Illinois: Charles Thomas)

Owens D A, 1980 "A comparison of accommodative responsiveness and contrast sensitivity for sinusoidal gratings" *Vision Research* **20** 159-167

Oyama T, 1962 "The effect of hue and brightness on the size illusion of concentric circles" *American Journal of Psychology* **75** 44-55

Riggs L A, Ratliff F, Cornsweet J C, Cornsweet T N, 1953 "The disappearance of steadily fixated test objects" *Journal of the Optical Society of America* **53** 110-120

Simonelli, N M, 1979 *The Dark Focus of Visual Accommodation: Its Existence, Measurement, and and Effects* Doctoral dissertation (unpublished), University of Illinois at Urbana-Champaign