Mach bands and depth adjacency*

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A luminance gradient was constructed consisting of four successive steps of decreasing luminance which were staggered in depth. With monocular viewing, all steps appeared in the same apparent depth plane, and clear Mach bands were visible. With binocular viewing, however, the steps appeared to be at different distances, and Mach bands were greatly attenuated or absent even though each monocular view contained an adequate stimulus for their perception. Implications of this finding for retinal accounts of brightness contrast effects are discussed.

In a recent study (Wist & Susen, 1973), it was found that the magnitude of simultaneous contrast in the Koffka ring illusion was a function of the depth separation between the test figure and the bisecting line used to induce contrast. It was found that the magnitude of the difference in perceived brightness between the two halves of the test figure was inversely related to the depth separation between the latter and the bisecting line.

Gogel & Mershon (1969) demonstrated an analogous effect for the Gelb phenomenon. The perceived brightness of a disk centered over a larger annulus varied inversely with the depth interval between these two stimuli. The results of these two studies, plus that of Mershon (1972), support the conclusion that simultaneous contrast is influenced not only by the lateral separation (or adjacency) of interacting stimulus components, but also by their depth adjacency. Since the proximal stimulus on each retina in all three experiments was adquate for producing contrast effects, but such effects were greatly reduced or eliminated with stereoscopic viewing, a strong central influence on simultaneous contrast is indicated. An account solely in terms of a retinal mechanism such as lateral inhibition is certainly not adequate in at least two instances of simultaneous contrast. The purpose of the present study was to extend the investigation of the effect of depth adjacency on simultaneous contrast to Mach bands. Ratliff (1965) has shown how nicely the concept of lateral inhibition at the retinal level can be used to explain Mach bands. Such an account would not by itself be adequate if it were found that depth adjacency affected the visibility of Mach bands. In the experiment reported here, a step-wise luminance gradient was constructed so that not only was a brightness change perceptible at the contours formed by the discontinuities in luminance, but also a depth interval. It was predicted that if depth adjacency affects the perception of Mach bands, binocular viewing of this luminance gradient ought to result in the perception of weaker bands than would monocular viewing.

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METHOD

Subjects

Seventeen male and nine female Franklin and Marshall College students served as Ss to fulfill one of the requirements of an introductory laboratory course in psychology. Each possessed a visual acuity of at least 20/20 in each eye (corrected by glasses if necessary), a stereoacuity of at least 32 sec of arc, and normal phorias all as measured with a Bausch and Lomb orthorater.

Apparatus

Ss sat in a darkened observation booth and looked through two apertures at a stimulus display immediately behind a square aperture located 125 cm away. Shutters on the outside of the booth controlled by E allowed either monocular (left or right eye) or binocular viewing. The display consisted of four adjacent overlapping vertical strips of white matte construction board (reflectance 32%). Each strip was 1 deg in width, and the vertical height in the visual field of all four strips was limited by the 5-deg square aperture. These strips were staggered in depth with the leftmost nearest and the rightmost farthest from S. Their physical spacing in depth was adjusted so as to produce a retinal disparity of 8 min of arc between successive strips (based on a mean interpupillary distance of 64 mm).

A luminance gradient was produced across the four strips by varying the angle of slant of each with respect to a light source (a cool-white, 15-W fluorescent tube) located directly behind and to the right of the square aperture. The luminance at the center of each strip was adjusted to be 85, 55, 35, and 15 fL from left to right, respectively. These luminances were reduced at the eyes by a factor of 10 by filters located behind the viewing apertures. When viewed binocularly, the strips appeared to be staggered in depth, with the leftmost nearest and brightest and the rightmost farthest and dimmest. When viewed monocularly, however, all four strips constituting the stepwise luminance gradient appeared to be in the frontoparallel plane just behind the square aperture. Mach bands were clearly visible. No texture was discernible on the strips when observed either binocularly or monocularly.

Procedure

Upon being seated in the viewing booth, S was read a standardized set of instructions concerning his task. First he was shown an example of Mach bands. For this purpose, the cover of the September 1972 issue of *Scientific American* was used (Ratliff, 1972). S was asked if the brightness within each of the successive strips in this illustration was uniform. All were able to respond correctly in the negative and to point to both the light and dark Mach bands. Afterwards, a mask made of white construction board was laid over the surface of the illustration such that only one strip at a time was exposed. S was asked if the brightness within the single exposed strip was uniform. All Ss were able to report correctly that is was. S was then told that he would be exposed to several similar displays that would be visible when he looked through the viewing apertures and that he would be asked to indicate, by using a 4-point scale, the degree to which the brightness within each of the four successive vertical strips was homogeneous. A "0" was to be used to indicate the complete homogeneity which they observed when the illustration was masked (no Mach bands), while a "3" was to be used to indicate the strongest inhomogeneity such as was observed in the unmasked illustration (strongest Mach bands).

Ss were then given two practice trials. For the first one, exposure was binocular and for the second, monocular (with the right eye for a random half of the Ss and with the left eye for the remainder). Attention was not called to the fact that S would be viewing the display either binocularly or monocularly, nor was S aware of the fact that shutters were being manipulated by E between trials. Ss were asked for their ratings after they had viewed the display for at least 15 sec. A 1-min interval separated each trial.

Two test trials followed the practice trials. These were administered exactly as the practice trials. The results obtained from these trials were used in the data analysis.

RESULTS

The mean ratings obtained for the test trials from the 26 Ss was 1.92 (SD 1.21) for binocular and 2.50 (SD 1.05) for monocular viewing of the Mach band display. A t test for related means indicated that this difference was statistically significant ($t = 2.375$, $df = 25$, $p < .025$). Of the 26 Ss, 17 rated the binocularly observed Mach bands as less strong, 5 Ss rated the monocularly observed bands as less strong, and 4 Ss rated binocularly and monocularly observed bands as equally strong. Significantly more Ss reported weaker bands with binocular than with monocular viewing ($z = 2.15$, $p = .016$, one-tailed test).

DISCUSSION

The results clearly support the findings of previous studies on the effects of depth adjacency on simultaneous contrast (Gogel & Mershon, 1969; Mershon, 1972; Wist & Susen, 1973). When the Mach band display was viewed binocularly, such that the successive steps in the luminance gradient appeared to be at different depth planes, the visibility of Mach bands was significantly reduced.

It should be stressed that, with binocular viewing, a perfectly adequate stimulus for the production of Mach bands existed in the proximal stimulus projected upon each retina. Furthermore, it cannot be argued that it was binocular viewing per se which reduced the visibility of Mach bands. We found no difference in the strength of Mach bands reported when Ss viewed a similar Mach band display constructed so that all steps in the luminance gradient were located in the same depth plane. Rather, the difference between binocular and monocular viewing is related to the difference in the perceived depth of the successive steps in the luminance gradient produced by retinal disparity.

What is the basis for this effect? One possible explanation is in terms of central inhibition. It might be argued that when the Mach band display is observed with retinal disparities of 8 min of arc between successive luminance steps, the resulting misalignment of discontinuities in luminance in the binocularly integrated view inhibits the bands because of overlapping excitatory and inhibitory receptive fields. It should be noted, however, that the 8 min of arc disparity between successive steps was well within the limits of Panum's fusion areas for the central retina (Ogle, 1962).

An account perhaps more compatible with the neurophysiological data is that the different depth planes represented in the display produce activation of different populations of spatially separated cortical units sensitive to receptive field disparity (Bishop, 1972; Wist & Freund, 1971). Since the contours providing the basis for the receptive field disparities are generated by luminance steps, there should also be an identical segregation in the cortical representation of brightness information. This would not be the case, of course, for monocular viewing. Here no receptive field disparity differences exist between successive luminance steps, and therefore, the cortical representation would preserve the lateral spatial adjacency between successive luminance steps. According to this account, only in this latter case would the spatial topography existing at the retinal level be preserved in the cortical projection. Thus, in this case, lateral inhibitory interactions such as described by Ratliff (1965) would be reflected at the cortical level.

A third account, not necessarily incompatible with the neural account outlined above, is in terms of the adjacency principle. As articulated by Gogel (1965), this principle states that the effectiveness of the interaction between stimuli in the visual field depends upon their perceived spatial separation either in the frontoparallel plane or in depth: the greater their spatial separation, the smaller their effectiveness. Mershon (1972), for example, found that the amount of induced simultaneous whiteness contrast between two surfaces in the visual field varied inversely both as a function of their lateral separation in the frontoparallel plane and their depth separation. It should be pointed out that the depth adjacency principle is not limited to depth produced by the retinal disparity cue. This principle, for example, would predict that, if the successive luminance steps in the Mach band display used in the present study were made to appear at difference distances due to, say the relative size cue, the same attenuation in the visibility of Mach bands ought to occur. Thus, this account is more general than that of the central inhibition hypothesis described above which is limited to the case of perceived depth resulting from the retinal disparity cue only. This account however, is not incompatible with one in which the cortical representation of information from various regions in the visual field reflects not only the lateral separations, but also the depth separations between objects independent of by what means the latter are produced.

The question remains as to whether depth adjacency effects exist for all instances of brightness contrast. Preliminary data obtained on the Hermann grid illusion suggests that it does not. A version of this illusion was constructed so that about 8 min of arc of retinal disparity existed between the intersecting white bars and the black ground. (The ground was made to appear behind the bars in depth by making a small number of pinholes in a sheet of aluminum foil which was rear projected. These pinholes did not prevent the appearance of the illusion at all in monocular viewing.) In this experiment, no difference in the darkness of the spots at the intersections of the bars were noted whether the bars and background appeared in the same or in different depth planes. Furthermore, a subsequent study[1] has shown that the effect of dark adaptation on the appearance of this illusion is exactly what one would expect if a purely retinal account of this illusion were appropriate. Jung and Spillmann (1970) have given such an account, which is compatible with all of the data to date on this illusion.

It is impossible at this point to specify just what may distinguish the Hermann grid illusion as an instance of brightness contrast from other such illusions. Clearly, the Gelb phenomenon (Gogel & Mershon, 1969), the Koffka ring (Wist & Susen, 1973), and Mach bands are greatly affected by depth adjacency. They are, therefore, not amenable to purely retinal accounts. It remains for future investigations to determine why the Hermann grid is resistant to a depth adjacency effect.

REFERENCES

Bishop, P. Neurophysiology of binocular single vision and stereopsis. In R. Jung (Ed.), *Handbook of sensory physiology*. Vol. VII/3, Part A. Berlin: Springer-Verlag, 1972.

Gogel, W. C. Size cues and the adjacency principle. Journal of Experimental Psychology, 1965, 70, 289-293.

Gogel, W. C., & Mershon, D. H. Depth adjacency in simultaneous contrast. Perception & Psychophysics, 1969, 5, 13-17.

Jung, R., & Spillmann, L. Receptive field estimation and perceptual integration in human vision. In D. B. Lindsley and F. A. Young (Eds.), *Early experience and visual information processing in preceptual and reading disorders.* Washington, D.C: National Academy of Sciences, 1970.

Mershon, D. H. Relative contributions of depth and directional adjacency to simultaneous whiteness contrast. Vision Research, 1972, 12, 969-979.

Ogle, K. N. The optical space sense. In H. Davson (Ed.), *Visual optics and the optical space sense.* Vol. 4. New York: Academic Press, 1962.

Ratliff, F. *Mach bands: Quantitative studies on neural networks in the retina.* New York: Holden-Day, 1965.

Ratliff, F. Coutour and contrast. Scientific American, 1972, 226, 90-103.

Wist, E. R., & Freund, H. J. The neuronal basis of binocular vision. In O. J. Gruesser and R. Klinke (Eds.), *Pattern recognition in biological and technical systems.* Berlin: Springer-Verlag, 1971.

Wist, E. R., & Susen, P. Evidence for the role of post-retinal processes in simultaneous contrast. Psychologische Forschung, 1973, 36, 1-12.

NOTE

1. Wist, E. R. Dark adaptation and the Hermann grid illusion. In preparation.

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Conditioned enhancement as a function of schedule of reinforcement

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Six rats were conditioned to press a bar for food reinforcement. During each session, there were six presentations of a 2-min light CS followed by a tone. The tone lasted until 2 sec had passed without a barpress. Then a sucrose-solution UCS was presented. When the ratio of response rate during the CS to response rate prior to the CS was calculated, it was found that the ratio was lowest when barpressing was reinforced on a VI 90-sec schedule, was at an intermediate value when barpressing was reinforced on a VI 4-min schedule, and was highest when barpressing was not reinforced.

Recently a number of experiments have investigated the interaction between operant and respondent behavior using a variation of the Estes & Skinner (1941) conditioned suppression procedure. In this variation, a positive unconditioned stimulus (UCS) such as food is used rather than a negative UCS such as shock. Several experiments using rats (Brady, 1961), pigeons (Herrnstein & Morse, 1957; LoLordo, 1971), and monkeys (Henton & Brady, 1970) have found that operant response rate was higher during the presence of a conditioned stimulus (CS) which preceded a positive UCS than during an interval of equal duration immediately prior to the CS. This phenomenon has been referred to as a conditioned enhancement. However, other experiments, using rats (Azrin & Hake, 1969; Hake & Powell, 1970; Van Dyne, 1971) and monkeys (Miczek & Grossman, 1971; Kelly, 1973) have reported response suppression during the CS. That is, response rate during the CS was lower than response rate during an interval of equal duration immediately prior to the CS. Meltzer & Brahlek (1970) have shown that CS duration plays a critical role in determining whether conditioned enhancement or suppression occurs. They found that short CS duration resulted in conditioned suppression while long CS durations produced conditioned enhancement.

The effect of CS duration seems to explain some of the differences in the results of these experiments but not all of them. For example, all experiments except the one by LoLordo (1971), in which conditioned enhancement was demonstrated, involved the use of CSs over 1 min long. All but two of the experiments in which conditioned suppression was demonstrated have used CSs less than 1 min long. One exception was the experiment by Miczek & Grossman (1971) in which the CS was varied across sessions from 15 sec to 3 min; the other was the experiment by Kelly (1973) in which the CS was 3 min long. These exceptions to the more common results were interesting because of some of the other experimental parameters which may have produced them. LoLordo (1971) could not produce conditioned suppression in the piegeon with short CSs of 20-sec duration when the Ss were reinforced on a variable interval (VI) 2-min schedule. Miczek & Grossman (1971) could not produce conditioned enhancement in the monkey with long CS durations when the Ss were reinforced on a VI 45-sec schedule. The monkeys in Kelly's (1973) experiment also failed to show conditioned enhancement after having been reinforced on a random ratio schedule, even though a VI 1-min schedule was used during test sessions. Although these experiments differed in many important aspects, there is clearly a possibility that frequency of reinforcement is an important variable affecting changes in response rate during the CS. Conditioned suppression did not develop when reinforcement frequency was low, and conditioned enhancement did not develop when reinforcement frequency was high.

Another reason for considering this hypothesis is that response rate during a CS that is followed by an electric shock UCS also changes in part as a function of the schedule of reinforcement. For example, Lyon (1963) studied conditioned suppression in the pigeon and showed that suppression was more complete when the schedule was VI 4 min than when it was VI 1 min. Blackman (1968) showed that suppression was greatest when both response rate and reinforcement frequency were low. If the processes producing conditioned enhancement are inversely related to the processes producing conditioned suppression, a reduction in