Color-selectivity in simultaneous motion contrast*

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Thirty-two Ss were required to estimate the apparent motion of stationary vertical lines viewed against a background of moving vertical lines when both patterns were seen by the same eye (monoptic conditions) or the center pattern was seen by one eye and the surrounds by the other eye (dichoptic conditions). The stationary lines appeared to be moving from right to left as the surrounds moved left to right. The simultaneous motion contrast found under monoptic conditions was maximal when the center pattern and the surrounds were the same color and was reduced when they differed in color. The surrounds had limited influence on the apparent motion of the center section under dichoptic condition, and the color relationship was no longer important. Related color selectivity has been reported for the motion aftereffect (successive motion contrast), and both sets of data can be attributed to inhibitory interaction (simultaneous in one case and successive in the other) among neural detectors tuned to wavelength as well as the direction of image motion.

Aftereffect paradigms have yielded data suggesting that at least some feature detectors in human vision are conjointly responsive to the color and spatial properties of stimuli. McCollough (1965) initially found that exposure to a vertical grating in orange light and a horizontal grating in blue light resulted in reports that vertical lines appear blue and horizontal lines look orange when black and white gratings were subsequently seen. In explaining these results, McCollough assumed that the color appearance of a vertical grating is given by the relative activity of edge detectors tuned to orange-vertical and blue-vertical and of a horizontal grating by orange-horizontal and blue-horizontal detectors. The color-vertical systems are normally in balance when a vertical grating is displayed in white light, and exposure to a colored vertical grating results in an aftereffect to the extent that one class of detector is adapted and the test grating shown in white light is represented by the unadapted system. Similar explanations have been offered of color aftereffects that are selective to the direction of image motion (Hepler, 1968; Stromeyer & Mansfield, 1970) and to the spatial periodicity of stationary gratings that are identical in orientation (Breitmeyer & Cooper, 1972; Lovegrove & Over, 1972; Stromeyer, 1972).

Spatial selectivity in color aftereffects is paralleled by color selectivity in spatial aftereffects. Thus, the tilt aftereffect, in which a vertical line appears tilted counterclockwise following exposure to clockwise tilted lines, is maximal when the inspection and test lines are the same color and is reduced when they differ in color (Held & Shattuck, 1971; Lovegrove & Over, 1973).

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Similar results have been obtained for the motion aftereffect (Favreau, Emerson, & Corballis, 1972; Lovegrove, Over, & Broerse, 1972; Mayhew & Anstis, 1972). Spatial aftereffects have been attributed to selective adaptation of neural feature detectors (see Coltheart, 1971; Over, 1971), and the above data support the earlier claim that conjoint analysis of color and spatial attributes is undertaken within visual processing.

Aftereffect paradigms entail successive presentation of inducing and test stimuli. In some cases, similar perceptual distortions (termed illusions rather than aftereffects) are produced by simultaneous display of the inducing and test stimuli. Thus, a stationary grating is seen as moving upwards following exposure to downward moving lines (successive motion contrast-aftereffect) or when viewed against a background of downward moving lines (simultaneous motion contrast-illusion). The motion aftereffect is considered to occur because some of the directionally selective motion detectors by which the stationary grating is normally signaled are temporarily in an adapted state following inspection (see Over, 1971). The illusion can be attributed to inhibitory interaction between the neural correlates of the stationary test pattern (normally signaled by the balanced response of opposed motion detectors) and the moving surrounds. The rationale is that the class of motion detector excited by the surrounds exerts inhibitory influence only over motion detectors with identical directional response within the part of the visual field stimulated by the stationary figure. The selective inhibition changes the balance in input between the opposed systems, and as a result, the test figure is seen as moving in the opposite direction to the surrounds.

The motion aftereffect is color-specific in that the extent to which stationary lines appear to move left to right following exposure to lines that move right to left is reduced when one pattern is seen in red light and the other pattern in green light (Favreau, Emerson, &

Fig. 1.

Corballis, 1972; Lovegrove, Over, & Broerse, 1972; Mayhew & Anstis, 1972). However, the magnitude of the aftereffect is unaffected by a color shift between the inspection and test stages when interocular transfer is studied by presenting the moving inspection grating to one eye and the stationary test grating to the other eye. Such data suggest that detectors tuned to color and motion receive exclusively monocular inputs, whereas motion detectors that can be excited binocularly are insensitive to color. In the present experiment, it is asked whether simultaneous motion contrast is color-specific in a similar manner. The Ss were required to estimate the apparent motion of a stationary grating surrounded by a moving grating, with the two gratings viewed in the same and in different colored light. Measures were taken with the two gratings viewed by one eye (monoptic condition) and by separate eyes (dichoptic condition). The analysis outlined above suggested that under monoptic conditions, the illusion would be maximal when the two gratings were the same color, but the color relationship would be unimportant under dichoptic conditions.

METHOD

Apparatus and Stimuli

The Ss were required to estimate the apparent motion of stationary vertical lines that were surrounded by vertical lines moving from left to right. The patterns were square wave gratings formed on separate oscilloscopes (Advance Model 2000S) by a method similar to the technique described by Campbell and Green (1965). The phosphor (P31) had broad spectral wavelength emission, and its intensity could be modulated linearly with applied voltage. The vertical y-axis was driven by the oscilloscope's internal time-base circuit at 2,000 Hz, and the electron beam was modulated by a variable square wave generator. By applying a synchronization pulse from this generator to the external trigger input of the time-base circuit, a grating could be locked in a stationary position. When the synchronization pulse was disconnected, the grating moved in a specific direction at a velocity dependent on the harmonic

relationship between the square wave and the fundamental 100-kHz sine wave.

Separate oscilloscopes displayed the gratings used as inducing and test stimuli, and a half-silvered mirror arrangement allowed the two gratings (each 4 cycles/deg) to be spatially juxtaposed in the visual field. The 1-deg circular test field was stationary, and the surround inducing pattern subtended 3 deg 20 min in diam and contained lines moving left to right at .5 deg/sec. Pilot testing with achromatic displays revealed that simultaneous motion contrast was maximal at these values.¹ Polarizing filters (Gerbrands HN-32) were used under dichoptic conditions to enable the surround grating to be seen by the left eye and the test grating by the right eye. To assist binocular fusion and overcome retinal rivalry, the S viewed dim nonpatterned light (1 deg in diam) of the same color as the test grating in the corresponding part of the visual field of the other eye. Under monoptic conditions, both gratings were viewed through the polarizing filters with the right eye. A fixation point was provided at the center of the test grating under monoptic and dichoptic conditions. The color of the gratings was manipulated using Wratten Filters 26 and 55, and neutral density filters were employed to match red and green patterns in space-average luminance at 6.53 cd/m².

Subjects

The majority of the 32 Ss were undergraduate students meeting a course requirement. All Ss had normal or corrected-to-normal vision.

Procedure

Three measures of simultaneous motion contrast were taken from each S under four color combinations (red-red, green-red, green-green, red-green) of the inducing and test gratings. Sixteen of the Ss made judgments under monoptic conditions and 16 under dichoptic conditions. Within each group, the order of testing between color combinations was counterbalanced across Ss. The Ss made judgments by moving a pen on a carriageway (outside the field of view) at the speed and in the direction in which the lines in the test grating appeared to be moving. The pen left a trace on recording paper moved at .25 cm/sec at right angles to the direction of the carriage, and the size of the illusion was given by the slope of the trace.² The Ss viewed the display for 15 sec before tracking apparent motion over a 15-sec interval. There was a rest period of 1 min between successive measures.

RESULTS

The mean pen displacement (in centimeters) in a 15-sec judgment interval is shown in Fig. 1 for the two viewing conditions and the four color combinations of the inducing and test gratings. An analysis of variance indicated that the magnitude of the illusion depended on the interaction between the surround and test color [$F(1,15) = 9.84, p < .01$]. Neither the surround color [$F(1,15) = .12, p > .05$] nor the test color [$F(1,15) = 1.28, p > .05$] were significant as main effects. The illusion was larger under monoptic than under dichoptic viewing conditions [$F(1,15) = 15.25, p < .01$], and the interaction between surround color, test color, and viewing conditions [$F(1,15) = 9.10, p < .01$] was also significant. Comparisons between means by Duncan's multiple range test showed that with monoptic viewing, there was greater simultaneous motion contrast when the two gratings were identical in color than when they

differed. The color relationship between the inducing and test gratings did not exert significant effect on judgments made under dichoptic conditions.

DISCUSSION

The results indicate that stationary lines appear in motion when surrounded by moving lines, and the distortion is larger when the two patterns are viewed by the same eye than when viewed by separate eyes and optically juxtaposed. In this respect, simultaneous motion contrast is similar to the motion aftereffect, for which partial interocular transfer occurs (see Wohlgenuth, 1911; Scott & Wood, 1965; Lovegrove, Over, & Broerse, 1972). Under monoptic conditions, color specificity is found for simultaneous motion contrast in the manner that has been demonstrated for the motion aftereffect; the illusion is greatest when the two gratings are identical in color but is reduced when they differ in color. This result is consistent with the claim made earlier that simultaneous motion contrast results from inhibitory interaction between feature detectors with similar response characteristics. Color selectivity in the illusion implies that inhibition occurs only between detectors that are tuned in the same way to motion and wavelength. Thus, if stationary lines in red light are normally signaled by a balance in the response of red/left to right and red/right to left detectors, there would be inhibition of the latter detectors when the surround lines move right to left in red light but not in green light. The reduction rather than the complete disappearance of the illusion when the center and surround gratings differed in color suggests that, in addition to color/motion-linked detectors, there are motion detectors that are nonselective to wavelength.

The McCollough aftereffects produced by prolonged inspection may persist for days (see McCollough, 1965; Hepler, 1968; Lovegrove & Over, 1972), and this factor seemingly poses problems for accounts of spatially selective color aftereffects and color-selective spatial aftereffects given in terms of neural adaptation. However, consideration of temporal variables becomes less important in establishing the mechanism of the McCollough effect if analogous perceptual distortions can be induced with simultaneous display of inducing and test stimuli. Such relationships would be expected if the proactive process of neural adaptation has a counterpart in inhibitory interaction occurring when topographically adjacent inducing and test stimuli are simultaneously presented. The present data reveal color specificity in simultaneous motion contrast under monoptic conditions similar to that demonstrated for the motion aftereffect (Favreau, Emerson, & Corballis, 1972; Lovegrove, Over, & Broerse, 1972; Mayhew & Anstis, 1972).

At least two other forms of illusion can profitably be studied by the approach adopted in the present

experiment. First, orientation aftereffects are color-selective (Held & Shattuck, 1971; Lovegrove & Over, 1973). In the associated geometrical illusion, which Blakemore, Carpenter, and Georgeson (1970) have attributed to inhibitory interaction among tilt detectors, two lines appear shifted from each other in orientation when they are joined to form an acute angle. This illusion should be reduced in magnitude when the inducing and test contours differ in wavelength. The second expectation is that color contrast will be orientation-specific when gratings are used as inducing and test stimuli in place of the traditional homogeneous fields. The McCollough effect is an instance of orientation selectivity in successive color contrast in that white lines appear red after exposure to green lines, with the color distortion occurring only when the two gratings are identical in orientation. In the case of simultaneous color contrast, a black and white vertical grating should appear a more saturated green when surrounded by a red vertical than by a red horizontal grating. This distortion would occur if the center is normally signaled by opposed red-vertical and green-vertical systems and the red-vertical center is inhibited by the red-vertical (but not by the red-horizontal) surrounds.

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NOTES

1. Measures obtained with achromatic gratings showed that the extent of simultaneous motion contrast depends on the velocity of the surround lines. Sixteen Ss were required to estimate the motion of a stationary grating (1 deg in diam and 4 cycles/deg) surrounded by an inducing grating (3 deg 20 min in diam and 4 cycles/deg) of lines moving from left to right. Both gratings were vertical. Each S made four estimates of the apparent motion of the center lines by the method described in the procedure section. Mean pen displacement varied with the velocity of the surround lines as follows: .5 deg/sec (22.56 mm), 1 deg/sec (19.09 mm), 2 deg/sec (5.20 mm), 4 deg/sec (0.49 mm). The difference between these means was significant [$F(3,45) = 35.32, p < .01$].

Simultaneous motion contrast was also selective to the difference in orientation between the center and the surround

gratings. The surround lines moved at .5 deg/sec from left to right at a direction at right angles to their orientation. Ten Ss were tested by the procedures described in the present paper, and each S made four estimates at five orientation values. Mean pen displacement varied with the orientation (relative to vertical) of the surround lines as follows: 0 deg (24.95 mm), 15 deg (16.76 mm), 30 deg (11.87 mm), 45 deg (1.67 mm), 60 deg (0.01 mm). These means differ significantly [$F(4,36) = 24.56, p < .01$].

2. This method of measuring perceived motion has been employed in several aftereffect studies, and it has been shown to have a test-retest reliability of +.83 (see Over & Broerse, 1973). Although inter-S differences are found in the overall extent of pen movement, Over and Broerse (1973) found that conversion of raw scores to a common base (e.g., percentage of largest pen displacement made by S) did not alter the overall trends found by analysis of variance. The same applied to the present data.

The measure of motion perception used in the present experiment was calibrated by requiring eight Ss to displace the pen at the same speed as the grating moving at known velocity. Each S made four judgments with the grating moving at 0, .50, 1.00, 2.00, and 4.00 deg/sec. The data were fitted by the function $y = .06x$, where y is the mean pen displacement in millimeters and x is stimulus velocity (deg/sec).

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