ences about the role of best friends in general.
9. E. Sutherland and D. Cressey, *Criminology* (Lippincott, New York, ed. 8, 1970), pp. 75–91.
10. For a recent critique, see G. F. Jensen, *Amer. J. Sociol.* **78**, 562 (1972).
11. I thank E. Kandel, E. Single, and D. Wilder for critically reading the manuscript and R. Marel, S. Paton, and A. Weber for technical assistance. Supported by PHS research grant DA00064. A preliminary communication of these results was presented at the Conference on the Epidemiology of Drug Use, Puerto Rico, February 1973, sponsored by the Schools of Public Health of Columbia University and of the University of Puerto Rico and the National Institute of Mental Health.

24 April 1973; revised 8 June 1973

Curvature as a Feature of Pattern Vision

Abstract. *Prolonged inspection of convex lines of one color and concave lines of another color can cause the appearance of oppositely colored aftereffects in curved, achromatic test lines. These effects, strongly dependent on radius of curvature, cannot be attributed to tilt or orientation. It is concluded that these results are not encompassed by models of the visual system that are based on rectilinear arrays and that curvature is a specific feature of human visual perception.*

McCollough (*1*) described adaptational effects that were dependent on the orientations of lines. Her subjects viewed a horizontal grating of one color, alternating with a vertical grating of another color, for a total inspection time of 2 to 4 minutes. Following this inspection, relatively long-lasting, oppositely colored aftereffects appeared in achromatic gratings of the same orientations. McCollough pointed out that these aftereffects were not conventional afterimages, since they were governed only by the orientations of the lines. She suggested that these aftereffects might depend on "color adaptation of orientation-specific edge-detectors" and cited neurophysiological evidence that edges are particularly effective visual stimuli (*2*). She also pointed out similarities between her observations and those of Kohler (*3*) and others involving long-term adaptation to wearing prismatic spectacles that produced fringes of color along an edge. These studies had also shown relatively long-lasting, oppositely colored aftereffects along light-dark edges.

Harris and Gibson (*4*) confirmed McCollough's basic finding and gave additional evidence that retinal afterimages could not account for the effect. However, they questioned the need for a concept as complex as that of an "edge-detector." Instead they advanced a "dipole" hypothesis as a minimal construct to account for all the color-contingent aftereffects that had been observed up to that time. The dipole "would receive inputs from two nonconcentric areas of the retina. Given a population of fatiguable dipoles with some variation in spectral sensitivity and in spatial relation of receptive areas, very few additional assumptions are necessary to deal with all data on the McCollough effect" (*4*, p. 1507).

I have discovered that rectilinear arrays (straight lines and edges) are not a necessary feature of patterns that generate color-contingent aftereffects. Curved lines will do nearly as well, provided that opposite directions of curvature are used for the two inspection patterns, as shown in Fig. 1. This result would not be predicted by the dipole hypothesis as it was originally stated (*4*). Nor is it consistent with explanations based on detectors for orientation of lines or edges (*1–3*). Some alternative concept, such as that of detectors for curvature, is evidently called for.

To generate the effect, the observer first looked for a few seconds at the center of the red pattern in Fig. 1, then shifted his gaze to the center of the green pattern, and thus continued the alternate inspection of the two for a period of 40 seconds. The inspection patterns were then switched off, the achromatic test pattern was switched on, and the observer was asked whether any color difference seemed to be present from one panel to another of the test pattern. If no color effect was reported, the inspection stimuli were turned on again and inspected for an additional 20 seconds, after which another test with the achromatic pattern was given. This alternation of inspection and testing was continued in a logarithmic series of increasing durations for as long as was necessary to establish the colored aftereffect with this particular curvature. Six different curvatures were used, one per day in random order, with each of four subjects.

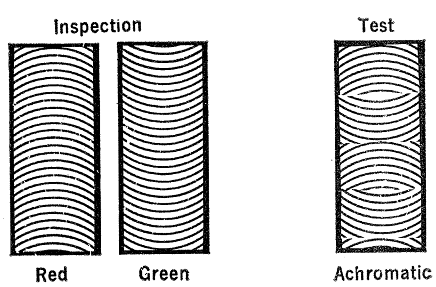

Fig. 1. Sample of inspection and test patterns used to evaluate curvature effects. The radius of curvature throughout this set of patterns is 4.5°. Note that the red inspection pattern has lines that are convex upward, and the green pattern has lines that are concave upward. After alternate inspection of these two patterns, the subject sees the corresponding curves on the test panels as greenish and pinkish, respectively. Each pattern is 13°8″ high and 5°26′ wide in angular subtense at the eyes with a viewing distance of 1 m. Patterns are on 35-mm slides projected through suitable red, bluish green, and achromatic dye filters so that the luminance of each pattern on the screen is approximately 6.8 mlam.

A summary of the individual results appears in Table 1 and median durations are plotted in Fig. 2. A "slight" effect was recorded when the observer reported that any panel of the test pattern had the appropriate appearance, namely, a coloration that was opposite to the one in the correspondingly curved lines during inspection. A "definite" effect was when the observer consistently reported that alternate test panels had the appropriate aftereffect colors. Note that there was relatively good agreement among the observers, and that the required inspection times were strongly dependent on radius of curvature.

It is clear that curvature-dependent colored aftereffects have been established. Brief inspections suffice to produce the effect with strong degrees of curvature, whereas inspection time rises steeply to 30 minutes or more as the lines approach a null condition in which they would all be straight and horizontal.

In a supplementary experiment, red and green patterns such as those shown in Fig. 1 were inspected for 15 minutes. At the end of that interval the entire series of six achromatic test patterns was presented together on the screen as shown in Fig. 3, and the subject was asked to rank them in order of the vividness of the colored aftereffects that appeared on each. Five subjects were used, and after a 15-minute inspection of strongly curved lines all of them rendered the expected judgment; namely, that more vividly colored aftereffects were seen on the test panels resembling those used for inspection than on those of weaker curvature. An unexpected result was obtained, however, on other days when the subjects had inspected colored patterns having a weaker curvature. They then reported no color at all, or only very weak coloration, on the test panels of the same weak curvature; but all saw more definite coloration on the panels of stronger curvature. Thus the curvature-induced colored aftereffects are by no means specific to the curvatures that are used for inspection. This finding implies that there are no curvature-analyzing units in the visual system that are specifically tuned to the weaker degrees of curvature. Perhaps the curvature analyzers are not tuned at all, but simply respond more vigorously as radius of curvature is diminished to some optimum value. The results shown in Fig. 2 indicate that the optimum radius lies at or below the lowest value (3°) used in these experiments.

It may seem that the effects I have attributed to curvature may instead arise from the differences in orientation or tilt that are present in increasing degree with patterns of stronger curvature. With fixation at the center of each pattern, the curved lines do have increasingly different orientations as they run out to the left or right edge of each pattern; and opposite orientational changes occur in the red and green inspection patterns. This argument seems to be all the more cogent because of the success with which models based on orientational channels and spatial frequency analyzers have dealt with the resolution of periodic linear arrays (*5*) and because of the electrophysiological studies emphasizing the tuning for line orientation in cells of the visual cortex (*2, 6*). However, the following arguments can be advanced against this position.

First, the subject always fixated the center of each pattern used for inspection. At this point every line has the same orientation or tilt as every other line; if one were to draw tangents to the curves they would all be horizontal lines. Second, along each horizontal border between achromatic test panels there seems to be an equally well-marked difference of color between the panels above and below it, whether the subject holds his fixation on the center of the border or lets his eyes wander to the right or left of center. Note that, in moving to the right, the fovea is confronted with orientations that are opposite to those found in moving to the left; that is, within any single panel the lines are of increasingly positive slope as the gaze moves horizontally in one direction and of increasingly negative slope as the gaze moves in the opposite direction. The orientational McCollough effect has been shown to be specific to the retinal location in which it is induced (*7*); thus the constancy of the colors along the border, as seen by the fovea under these conditions, is not compatible with an orientational explanation of aftereffect colors. Third, orientational explanations would predict that the strongest color effects should be found with curves having orientations identical to those used for inspection (*8*). This is not the case, however; when patterns of weak curvature are inspected, the most vivid aftereffects are seen on test patterns having a stronger curvature.

The dipole hypothesis, attractive because of its simplicity, nicely explained the original McCollough effect (*4*). Given that each dipole received input from two separate areas on the retina, it would readily be stimulated by a light-dark border falling between them and oriented at some angle not too far from a perpendicular to the axis of the dipole. To distinguish a concave or convex border from a straight one, the two areas of the dipole would have to overlap one another and could not be perfectly symmetrical in the excitatory

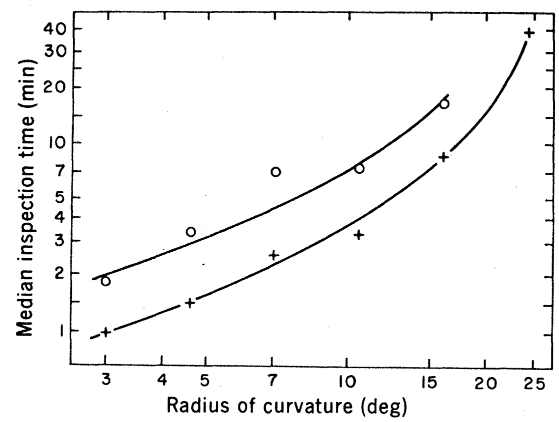

Fig. 2. Inspection times for the establishment of colored aftereffects as a function of curvature. Each point is the median time for four subjects to attain a slight (pluses) or definite (circles) appearance of color on the achromatic test panel.

Table 1. Inspection times necessary to build up a slight or definite colored aftereffect on the basis of curvature.

Subject	Time (minutes) with a visual angle of					
	3°	4.5°	7°	10.5°	16°	24°
			Slight effect			
A.G.	1.5	2.3	1.9	3.4	7.2	24.7
R.J.	0.7	1.0	1.9	2.3	5.0	
L.R.	1.5	1.0	3.4	3.4	11.3	37.2
R.S.	0.7	3.4	4.7	7.2	11.3	
			Definite effect			
A.G.	3.4	3.4	4.7	7.5	37.2	
R.J.	1.5	3.4	7.2	3.4	7.5	
L.R.	2.3	1.5	7.5	7.5	16.9	
R.S.	1.0	5.0	7.2	10.9	16.9	

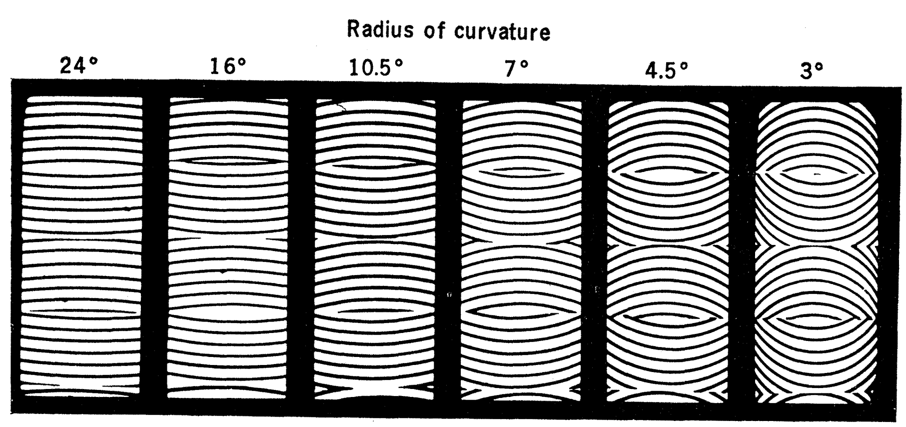

Fig. 3. Series of achromatic test patterns used for ranking the strengths of curvature-contingent colored aftereffects. Patterns have the same dimensions as those in Fig. 1. The most vividly colored aftereffects appear on the most strongly curved patterns (3° or 4.5°) regardless of the pattern previously inspected.

or inhibitory portions of their receptive fields.

The original McCollough concept of an edge detector, although somewhat more complex than a dipole, was likewise presented as a straight-line model. It assumes that direction of orientation is the main property of an edge (*1*). To add direction of curvature as another property to be analyzed by edge detectors would be to raise formidable questions about the explanatory value of this construct.

A particularly attractive hypothesis, that of channels specialized for the detection of the spatial frequency of lines in a grating (*5*), can easily encompass many of the results obtained by the McCollough procedure. Yet it, too, is a model based on rectilinear arrays that are tuned for direction of orientation. Inasmuch as the curvature-dependent aftereffects reported here cannot be attributed to orientation, that model also fails to provide any explanation for my results.

Where does this leave us? Neurophysiologists are finding that the processing of visual information takes place at all levels within the visual pathways (*9*). Such features as color, orientation, spatial frequency, contrast, depth, and motion are selectively effective as stimuli for specialized neural detectors. Experiments based on the McCollough effect, although restricted to the case of straight-line arrays, have already demonstrated response contingencies between color and tilt or orientation (*10*), spatial frequency (*8*), and direction of motion (*11*) of the lines. The results reported here point the way toward more general feature analysis. In particular they may stimulate electrophysiologists to look for cortical cells for detecting the degree and direction of curvature (*12*).

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12. D. H. Hubel and T. N. Wiesel [*J. Neurophysiol.* **28**, 229 (1965)] have described hypercomplex cells in the visual cortex of the cat that are of particular interest here. Some of these cells respond preferentially to angles and curves. As the authors put it, these cells "can, in a sense, serve to measure curvature; the smaller the activating part of the field, the smaller the optimal radius of curvature would be." Similar cells were also found in the monkey (*6*). Such cells, if they were also selectively responsive to colors, could well mediate the effects described in this report. K. D. White reports that "aftercolors from inspecting chevron patterns obey similar principles to the aftercolors from inspecting patterns of curved lines" (program of the annual meeting of the Association for Research in Vision and Ophthalmology, Sarasota, Fla., May 1973, p. 35).
13. These experiments were conducted in major part at the Physiological Laboratory of the University of Cambridge while the author was a Guggenheim Fellow on sabbatical leave from Brown University. I think Dr. Fergus W. Campbell for laboratory facilities and C. Hood and P. Starling for technical assistance.

13 December 1972; revised 1 June 1973

Hurricane Seeding Analysis

In the article "The decision to seed hurricanes" by Howard *et al.* (*1*) it is stated in the subtitle that "On the basis of present information, the probability of severe damage is less if a hurricane is seeded." In my opinion present knowledge does not support such a statement because the results of studies of this problem do not provide a unique answer. Consequently, no conclusions can presently be made about the economic effects resulting from seeding hurricanes.

The data available from seeding experiments (such as those from Hurricane Debbie and possibly Hurricane Ginger) are too few for a statistical analysis to yield confident conclusions. Furthermore, the results of the numerical model studies referred to by Howard *et al.* conflict with results which I reported (*2*). In fact, if the method of Howard *et al.* is applied to my results, the conclusion reached is the opposite of that reached by Howard *et al.*, as I show below.

The standard deviations adopted here are the same as those in Howard *et al.* for all three hypotheses concerning the effect of seeding (H_1, reduction of the maximum wind; H_2, no effect; H_3, increase of the maximum wind). The probability distribution for the wind speed if the hurricane is seeded, w', if H_2 is true, is the same as that of Howard *et al.* (*3*):

$$P'(w'|H_2) = P(w'|H_2) = P(w) = f_N(100\%, 15.6\%) \quad (1)$$

where w is the wind speed of the unseeded hurricane (*4*).

Using the results of the numerical experiments presented in (*2*) I assign the following probability distribution to w' for the case that H_3 is true

$$P'(w'|H_3) = f_N' \,(107\%, 18.6\%) \quad (2)$$

The probability distribution employed for w', if it is considered that H_1 is true, is

$$P'(w'|H_1) = f_N' \,(95\%, 18.6\%) \quad (3)$$

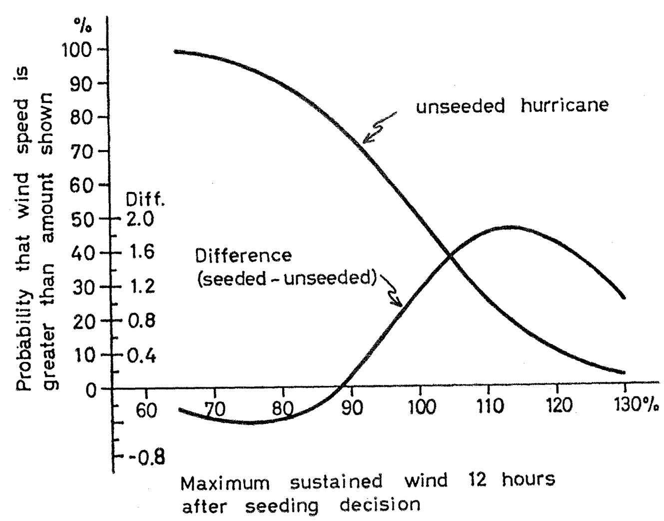

Fig. 1. Probability distribution on 12-hour wind changes for the unseeded hurricane, and the difference in probability distributions between the seeded and the unseeded hurricane.