Difference information in brightness perception*

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Contour information generated by moving retinal images has been shown by others to be the principal determinant of perceived color. The data presented here show that, for brightness, this information reflects only differences between adjacent stimulus areas. The entire distribution of difference information from contours in the visual field must be specified in order to predict the brightness at any point.

Considerable evidence suggests that temporal and spatial changes of the light striking the retina are the principal determinants of brightness and hue. Some of the most compelling of this evidence has come from experiments with stabilized retinal images. Krauskopf (1963), and later Gerrits, deHaan, and Vendrik (1966) and Yarbus (1967, p. 79), demonstrated that a stabilized disk superimposed on an unstabilized background takes on the color—the hue, saturation, and brightness—of the background.

To explain this result, Krauskopf suggested that the colors of areas lying between contours in the visual field were determined by responses occurring at the contours alone. These responses are generated by the temporal changes of stimulus spectral characteristics and illuminance on the retina which result when image contours are swept across the retina by eye movements. The perceived colors of areas not undergoing temporal changes are determined by the change information generated at the surrounding contours. The argument is central to this paper and is given in greater detail in the original papers (Krauskopf, 1963, 1967).

Evidence consistent with Krauskopf's explanation comes also from experiments with unstabilized retinal images (Craig, 1966, p. 95; O'Brien, 1958). The distributions used in these studies have very shallow spatial luminance gradients and abrupt luminance steps. As Cornsweet (1966) pointed out, very gradual spatial changes of luminance are similar to the contours in stabilized images in that both fail to generate the temporal changes on the retina required for spatial brightness changes to be perceived.^{1,2} Krauskopf (1967) extended this argument to shallow spectral gradients and hue changes.

Assuming that contour responses or change information determines the

perceived color distribution of the entire field, one important question is, what information is carried in the responses generated by moving contours in the retinal image? There are two immediately available hypotheses: (1) The contour responses may provide the organism with information about the absolute characteristics of the light falling on either side of the contour, or (2) the responses generated by the temporal changes might reflect only the differences across the contour.

According to the first hypothesis, which we call the absolute information hypothesis, the perceived colors are directly determined from the spectral compositions and intensities of the light, modified only by local contrast and adaptation effects. The resulting colors are extrapolated from the contours to the enclosed areas where there is no temporal change in the stimulus, and therefore no change information.

According to the second hypothesis, which we call the difference hypothesis, the contour responses provide change information only. When a point on the retina is traversed by a contour, the temporal change on that point is simply the difference between the spectral compositions and illuminances of the light on the two sides of the contour. The difference information alone allows only the specification of the relative colors on the two sides of the contour. The resulting perception is then extrapolated to the enclosed unchanging areas. Only the relation between the various parts of the visual field, the relative color distributions, is specified by this hypothesis. How this distribution is located in a color space is not specified.

The purpose of the present paper is to discriminate between these two hypotheses with respect to one aspect of color, brightness. Several spatial luminance distributions are presented for which the corresponding perceived brightness distributions are found to be in accord with the difference hypothesis and to contradict the absolute information hypothesis.

METHOD

Nine different spatial luminance distributions were produced by placing appropriately cut sectors of black and white on a disk which was rotated at a rate well above that required for flicker fusion. The luminances of the black and white materials under the lighting conditions of the experiment were measured with a Macbeth illuminometer, and the luminance distributions used are described with the results. The disks were viewed against a near-black background and were uniformly illuminated by floodlamps. The Ss were graduate students and faculty of the psychology department. At least five Ss viewed each disk.

For each spinning disk, the Ss were asked to describe the relative brightness distribution, indicating the locations and directions of all brightness changes, and ordering the brightnesses of the uniform portions of the distribution. Since ordinal relations among the bands on the disks are sufficient to test the hypothesis under consideration here, no attempt was made to determine the magnitude of the brightness differences.

RESULTS

The stability of the observations was such that the only variability in the Ss' reports was with respect to Mach-band-like effects at each contour. Some Ss reported them more than others. All other aspects of these reports were identical for all Ss. Accordingly, the data are reported in the form of diagrams constructed from the Ss' descriptions incorporating the relative brightnesses reported and the locations and directions of brightness changes. The small Mach-band-like border-sharpening effects are not relevant to our discussion and will not be discussed, although they have been sketched into Fig. 1a to indicate the approximate spatial extent of the effects. They have been omitted from the other figures for the sake of clarity.

The nine luminance distributions used are presented in the left-hand columns of Figs. 1 and 2. Each abscissa is distance in visual angle along the radius of the disk. The luminance corresponding to each point on the radius is plotted as the ordinate. The relative brightness distributions constructed from the Ss' reports are shown in the right-hand columns of Figs. 1 and 2. Each abscissa is the same as for the luminance distributions, and the relative brightness at each point is indicated on the ordinate.

REPLICATION OF O'BRIEN'S RESULTS

Results reported by O'Brien (1958) which are of importance to this paper were

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Fig. 1. Spatial luminance distributions (left) and corresponding brightness distributions (right) along a radius of the spinning disk. Each luminance distribution begins at 10 mL on the extreme left. The ordinate in the brightness column indicates only relative brightness within each subfigure.

replicated. The luminance distributions used are illustrated in the left columns of Figs. 1a, 1b, and 1c.

The moving (due to eye movements) retinal image of the luminance step in Fig. 1a produces contour information. This contour information determines the brightnesses of the areas immediately adjacent to the contour, and those brightnesses are extrapolated to the left and right of the contour where no contour responses are generated. Thus, a high luminance area which changes abruptly to a low luminance area is seen as a light band next to a darker band.

In Fig. 1b, the gradual luminance change does not produce large enough temporal changes on the retina to give a brightness change in the same location. Accordingly, the entire distribution is perceived as uniform. The same is true for the gradual change in Fig. 1c, while the abrupt luminance step in that figure gives rise to an abrupt brightness step. Since the gradual increase of the luminance to the right of the step is not perceived, the resulting perception is very similar to the brightness distribution of Fig. 1a, even though the difference between the luminances at the extreme right and left sides of the distribution is in the opposite direction from that of 1a. O'Brien's data replicate, and the results are impressively robust.

According to the absolute information hypothesis, the contour information in Figs. 1a and 1c indicates that the only spatial change in each distribution is at the center. This contour information indicates that the brightness immediately to the left of the contour is some absolute value, e.g., 10, on the S's brightness scale and that the brightness on the immediate right of the contour is another value, e.g., 5. These values are then extrapolated to the adjacent areas where there is no change information.

Applying the difference information

hypothesis, the contour information from the abrupt luminance step does not indicate the absolute brightness values near the step, but indicates only that the brightness on the immediate left is five brightness units greater than that on the immediate right. The brightness relations determined by this information are also extrapolated to the adjacent areas where there is no contour information generated. Since the contour information does not reflect the absolute luminance levels under the difference information hypothesis, exactly the same contour information might be generated by any of a large number of luminance steps, each starting

from a different luminance level on the left of the contour. Due to the nonlinearity of the visual response, however, the luminance difference required to produce contour information indicating a brightness step of any given size is presumably a function of the absolute luminance level.

Either hypothesis accounts for the data discussed above. The predictions of both hypotheses are identical with respect to the appearance of areas lying immediately on either side of a single unperceived stimulus change, whether produced by stabilization or blurring. But when one considers the perceptual distributions corresponding to stimulus distributions which contain several contours, the predictions of the two hypotheses are different.

MULTIPLE CONTOUR DATA

For our experiments, we used a luminance distribution closely related to that in Fig. 1c. This distribution, first described by Cornsweet (1965, p. 75), is illustrated in Fig. 2a. The only luminance gradient steep enough to give rise to brightness changes is the abrupt luminance step in the center of the distribution. The resulting perception is an "artificial contour" similar to O'Brien's, and it is predicted by either of the hypotheses.

When one places three or more of these "artificial contours" side by side (Fig. 2b), the predictions of the two hypotheses differ. According to the absolute

Fig. 2. Spatial luminance distributions (left) and corresponding brightness distributions (right) along a radius of the spinning disk. Each luminance distribution begins at 10 mL on the extreme left. The ordinate in the brightness column indicates only relative brightness within each subfigure.

information hypothesis, the contour information generated by each of the abrupt luminance steps specifies that the area to the immediate left of the contour is of a given absolute brightness which is greater than the absolute brightness of the area to the immediate right of the contour. These brightnesses are then extended to the adjoining areas where there is no contour information generated. Since the contour information bounding the band marked "A" in Fig. 2b is identical to the contour information bounding the band marked "B," this hypothesis predicts that the same brightness distribution will be perceived across each of the two bands.

According to the difference information hypothesis, the only information contained in the contour responses to distribution 2b is that the area to the left of each abrupt luminance change is a given number of units brighter than the area to the right. Since the absolute stimulus levels are not indicated by the contour information under this hypothesis, the pattern of contour information generated by Fig. 2b is identical to that of a series of rectangular luminance steps (as in Fig. 2c). Reading arbitrarily from left to right in Figs. 2b and 2c, there is no contour information until the first abrupt luminance step is reached. This step indicates that the area to the immediate left of each contour is brighter than the area to the right by a specified number of brightness units. This information is extrapolated to the right until further contour information is reached. At the second abrupt step there is again information indicating that the area to the left of the contour is brighter than the area to the right by a specific amount. This new level is then extrapolated to the area to the right of the second contour until further contour information is reached, etc. Thus, the difference information hypothesis predicts that the luminance distribution of Fig. 2b will give rise to a perception qualitatively identical to that of Fig. 2c. As the right-hand column of Fig. 2b shows, this was the reported relative brightness distribution. The contour information generated by the abrupt luminance steps appears to indicate only the magnitude and direction of the stimulus change, not the absolute level from which the change occurs. The example illustrates that all of the contour or change information in the field must be considered in determining the brightness at any given point.

The multiple contours need not all be "artificial contours" for the predictions of the two hypotheses to differ. The shallow luminance gradient is necessary only to provide unperceived stimulus changes so that the brightness distribution differs

from the luminance distribution. When one superimposes bands of equal gray on the two sides of the distribution in Fig. 1a, the usual simultaneous contrast effect is observed (Fig. 2d). On the other hand, when one superimposes the same bands on the two sides of the distribution in Fig. 2a, as illustrated in Fig. 2e, brightnesses of the superimposed bands differ in the opposite direction. The band superimposed on the brighter side appears brighter than does the band on the darker side. Prediction of this result from the difference information hypothesis is straightforward. The contour information from the contours of the two superimposed bands indicates that the bands are equally different from their backgrounds. The "artificial contour," however, indicates that the background of the left band is brighter than the right band. The absolute contour information hypothesis predicts that the two bands should be equal in brightness since all of the contour information of the two bands is the same.

In Fig. 2f, the equal-luminance bands are superimposed on backgrounds of unequal luminance. The shallow gradient, however, does not generate contour information. Ignoring simultaneous contrast for the moment, the absolute contour information hypothesis predicts that the two bands should once again be equal in brightness since the information generated by the contours of each band reflects the absolute luminance level of that band. The difference information hypothesis predicts that the left band should be darker than the right band since the contour information indicates that the left band differs from its background by less than the right band differs from its background. The absence of contour information from the shallow gradient between the bands, however, indicates that the background for the two bands is of the same brightness. The left band must therefore appear darker than the right. As indicated in the right-hand portion of Fig. 2f, this was the Ss' report.

Since the left band in Fig. 2f lies against a more luminous background than the right band, one might predict that it should be darker than the right due to simultaneous contrast. If the absolute information hypothesis is correct and the effect is entirely due to simultaneous contrast, the brightnesses of the two bands in Fig. 2d should be equal to those of the corresponding bands in Fig. 2f. However, when the Ss viewed the two distributions on disks side by side and directly compared the brightnesses of the four bands, they reported that Band Y was the darkest of the bands and that Band Z was the lightest. The brightness difference between Bands Y

and Z was, therefore, greater than that between W and X. This is in accord with the prediction of the difference information hypothesis, but is clearly in conflict with the prediction of the absolute information hypothesis.

CONCLUSION

The data reported here support the hypothesis that the brightness information generated by moving contours is difference information only, and the absolute information hypothesis is rejected. Krauskopf (1967) suggested that the colors of areas between contours are determined by the responses occurring to the contours. The observations reported here suggest that such responses provide information reflecting only the stimulus differences across contours. The evidence we present concerns only brightness, and further experimentation must determine whether hue and saturation information generated by contours similarly indicates only color differences.

Current theory bases color appearances on the absolute specification of the stimulus, suitably transformed to account for the operation of adaptation and contrast. The difference information hypothesis, on the other hand, implies that the absolute characteristics are, instead, functionally related to difference responses intermediate between the stimulus and the color appearance. These difference responses are further processed to yield the spatial distribution of perceived color. Under conditions where all of the spatial stimulus changes are represented in the distribution of difference information, as in the case of virtually all classical psychophysical color experiments, both of these approaches will yield the same predictions. When this is not the case, as in the situations described here, the predictions of the classical approach are not supported by the data.

REFERENCES

- CORNSWEET, T. N. In F. Ratliff (Ed.), *Mach bands: Quantitative studies on neural networks in the retina*. San Francisco: Holden-Day, 1965. Pp. 74-76.
- CORNSWEET, T. N. Stabilized image techniques. In M. A. Whitcomb (Ed.), *Recent developments in vision research*. Washington, D.C.: National Academy of Sciences, National Research Council Publication No. 1272, 1966. Pp. 171-179.
- CRAIK, K. J. W. *The nature of psychology: A selection of papers, essays, and writings*. Edited by S. L. Sherwood. Cambridge, England: University Press, 1966.
- GERRITS, H. J. M., deHAAN, B., & VENDRIK, A. J. H. Experiments with stabilized retinal images: Relations between the observations and neural data. *Vision Research*, 1966, 6, 427-440.
- KRAUSKOPF, J. Effect of retinal image

- stabilization on the appearance of heterochromatic targets. *Journal of the Optical Society of America*, 1963, 53, 741-744.
- KRAUSKOPF, J. Heterochromatic stabilized images: A classroom demonstration. *The American Journal of Psychology*, 1967, 80, 634-637.
- O'BRIEN, V. Contour perception, illusion, and reality. *Journal of the Optical Society of America*, 1958, 48, 112-119.
- YARBUS, A. L. *Eye movements and vision*. New York: Plenum Press, 1967.

NOTES

1. In addition to reducing temporal changes produced by eye movements, blurring the contours of the stimulus results in less stimulation of the Mach band (border-sharpening) mechanism. This may further reduce the effectiveness of the illuminance

change in producing a brightness change.

2. In this paper, the terms "change information" and "contour information" refer to responses generated by gradients sufficiently steep to generate suprathreshold temporal illuminance changes on the retina regardless of whether the resulting percept is a sharp contour or a more gradual spatial color change.

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