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Contrast and assimilation in the perception of brightness

(vision/retinex/neural computation/retina/visual cortex)

ROBERT SHAPLEY AND R. CLAY REID

Rockefeller University, 1230 York Avenue, New York, NY 10021

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ABSTRACT **The rapid estimation of the brightness of objects is one of the nervous system's major visual tasks. Exactly how the eye and brain perform this basic task is still not understood. Two mechanisms that contribute to human perception of the brightness of objects have been identified previously: (*i*) the visual response to physical contrast and (*ii*) assimilation. Use of a unique visual display device allowed us to measure the relative importance of these two mechanisms. The present results reveal that assimilation is about half as effective as physical contrast in determining the apparent brightness of objects. These results imply that previous theories of vision—for instance, the retinex theory—will have to be revised; the importance of physical contrast must be weighted more strongly.**

There appear to be two antagonistic mechanisms in the human visual system that are used for estimating the brightness of reflecting objects. One is a local, presumably retinal, neural mechanism that responds to the physical contrast between an object and its background (1–4). The other (presumably cortical) mechanism, which is responsible for the classical psychological phenomenon of assimilation (5–8), makes an observer's perception of the brightness of an object covary with the apparent brightness of the object's surroundings. Using a unique electronic visual display instrument (9), we have been able to obtain psychophysical measurements of the relative contributions of these two opposing neural mechanisms to the neural computation of brightness.

Other things being equal, the subjective impression of an object's brightness is monotonically related to the object's luminance, the amount of physiologically effective light per unit area of the object (10). However, when other things are not equal—in particular, the luminance distribution of the surroundings—an object's brightness is not simply related to its luminance. The apparent brightness to a large extent depends on the physical contrast between the object and its surroundings (1–4). In this paper we will define the physical contrast at a border between two areas of luminances L_1 and L_2 to be $C = 2(L_2 - L_1)/(L_1 + L_2)$. This is the variation in luminance divided by the average. In the typical situation of an object of low contrast on a background, this definition has approximately the same value as that of the Weber contrast (cf. ref. 4): $C_W = (L_{object} - L_{background})/L_{background}$. Note that contrast as we have defined it is a signed quantity. Also it can be treated as a function of position and thought of as the local contrast in a small region of visual space. The reason for the dependence of brightness on contrast probably comes about because the visual system associates brightness with reflectance and not simply luminance (11–13). Though an object's luminance may change with lighting conditions, its reflectance is an illumination-invariant property of the object. The physical contrast of a reflecting object on a reflecting background only depends on the reflectances of object and background, and thus it makes sense that contrast should be a good cue for brightness.

The second mechanism, the assimilation process, tends to oppose visual responses to contrast. Classically, assimilation has been conceived of as the psychological tendency for an object to take on the color of its surroundings. In brightness perception this means that a gray object on a black background will tend to look blacker than the same gray object on a white background, other things being equal. Thus, to some extent assimilation adds the brightness of a background to the brightness of an object on the background (5, 12, 13). The contrast process is subtractive; the assimilation process is additive.

Previous experiments have left unresolved the question whether perception of brightness is more strongly influenced by contrast or assimilation. In classical experiments on the effect of background illumination on brightness, only background luminance was varied (1, 2). This produced changes both in physical contrast and in assimilation. A related problem is inherent in Helson's study of assimilation: when brightness was varied, physical contrast was not controlled (5). Thus, although the presence of assimilation was demonstrated in such experiments, its magnitude could not be estimated because of the opposing effect of contrast. Similar uncontrolled variation of physical contrast occurs in the demonstrations of Land and McCann (12, 13). We have attempted to dissect the effects of responses to contrast from the process of assimilation by a choice of visual test stimuli in which *contrast was fixed* while brightness (and therefore assimilation) varied. This was done by producing brightness differences in background areas of equal luminance, by means of brightness induction from an "outer" background.

METHODS

Visual patterns were produced on the screen of a Tektronix 608 monitor (P4 white phosphor) with an electronic visual stimulator (9) under the control of a PDP 11/23 microcomputer. The instrument produced a 10 × 10 cm raster display: 256 lines per frame, 256 picture elements (pixels) per line, 270 frames per sec. It also produced four spatial luminance profiles that could be mapped into each of the 65,536 (256 × 256) pixels. The mapping was controlled by the values in a 65,536 × 2 bit memory, the values of which set the state of a fast electronic switch at a rate of 20 MHz. The physical contrast on the screen was controlled by depth-of-modulation values, for each spatial profile, sent to the instrument by the computer. In all experiments mean luminance on the screen was 100 cd/m^2, and the screen was viewed binocularly at a distance of 1 m.

RESULTS

The basic scheme of the experiments is illustrated in Fig. 1, which is also a demonstration of some basic phenomena of brightness perception. The spatial profiles of Fig. 1 *Upper*

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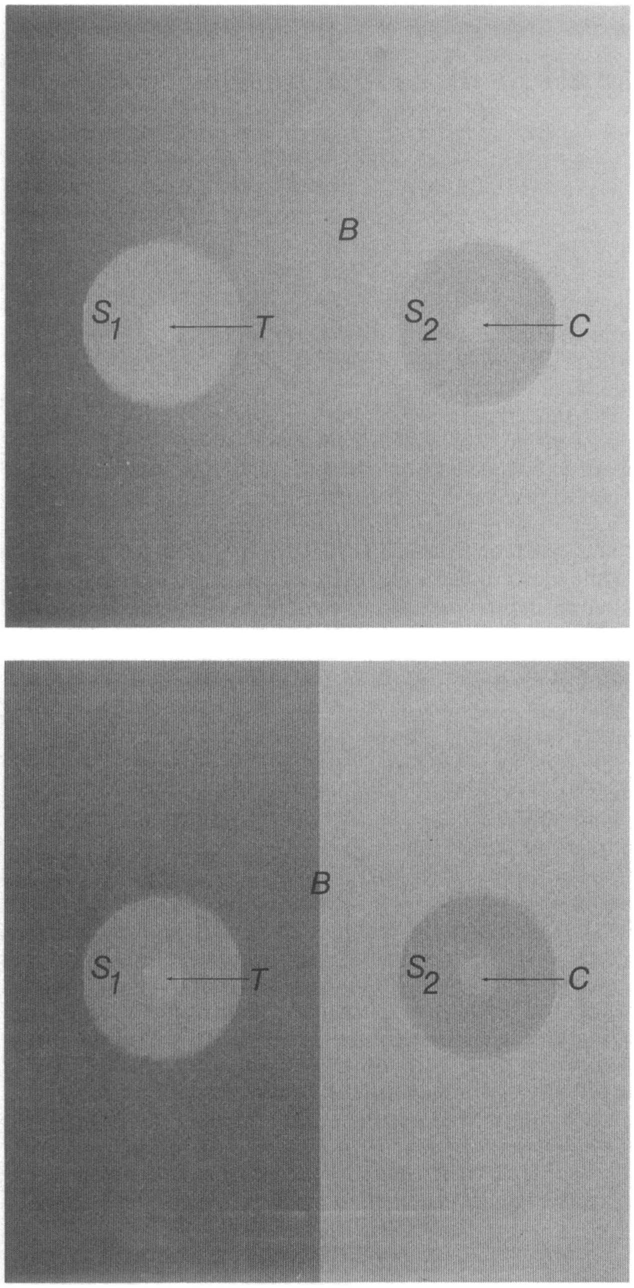

FIG. 1. (*Upper*) Photograph of the visual stimulus on the Tektronix 608 monitor. The area labeled B is the outer background; it is a linear gradient or ramp of luminance. S_1 and S_2 are the inner backgrounds surrounding the test spot labeled T and the comparison spot labeled C. In this picture C and T have the same luminance and are set to be of 0.12 contrast with respect to the inner backgrounds, S_1 and S_2, which are equal in luminance to each other and equal in luminance to the midpoint of the picture. The average contrasts of S_1 and S_2 with B were +0.25. (*Lower*) This is another photograph of a similar configuration but here the outer background B is a bipartite field. The contrasts of B with S_1 and S_2 and those of C and T with S_1 and S_2 are the same as in *Upper*.

and *Lower* are indicated in Fig. 2 *Upper* and *Lower*. The outer background is labeled B. In Fig. 1 *Upper*, the outer background is a linear gradient or "ramp" of luminance from left to right. The outer background in Fig. 1 *Lower* is a bipartite field or square wave profile. The inner backgrounds are areas of equal luminance and are labeled S_1 and S_2 for left and right, respectively. The luminance of S_1 and S_2 was L_0, the mean luminance of the outer background B. The centers of S_1 and S_2 were 2° 52′ apart and both had a radius of 43′ visual angle.

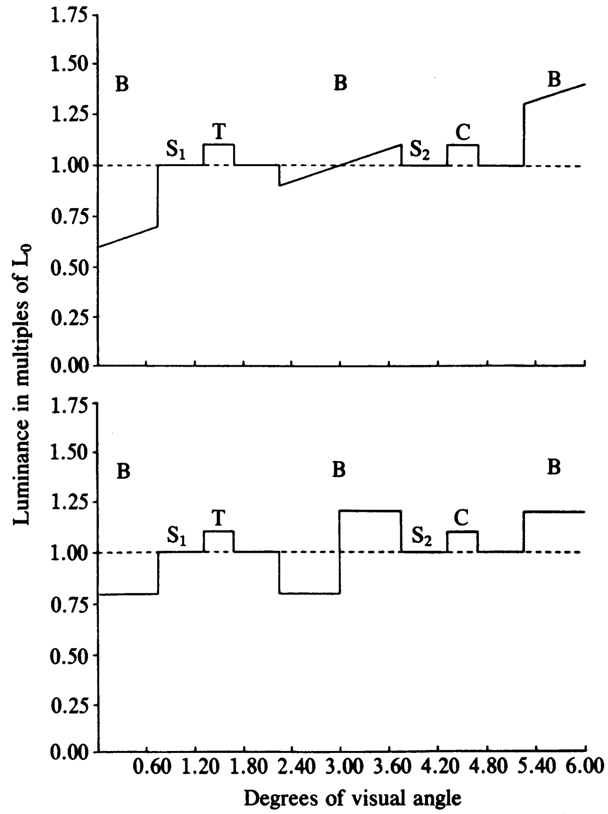

FIG. 2. Luminance profiles of the visual stimuli taken along a line through the midpoints of the test and comparison spots. Regions labeled as in Fig. 1. (*Upper*) Luminance ramp in the outer background. (*Lower*) Bipartite field in the outer background.

The circular test spot T (11′ radius) was placed on background S_1, while a comparison spot C (also 11′) was placed on background S_2. Thus, the distance between the border of the test spot and the border of its background was about ½° of visual angle, as it was also for the comparison spot.

In Fig. 1 the luminance of spots T and C were set equal to a value 12% higher than L_0. Since the luminance of S_1 equals the luminance of S_2, the physical contrast around the border of T is identical to the contrast of C. To the extent that T and C look identical in brightness, their brightnesses are determined solely by local contrast. To the extent that T and C appear to be of different brightness, assimilation is influencing perceived brightness. T appears brighter than C for all of our subjects. Therefore, Fig. 1 is a demonstration of the existence of assimilation in brightness under conditions of equal local physical contrast.

To estimate the strength of the assimilation process quantitatively, brightness matching of spots T and C was employed. Two subjects, the authors, performed a complete set of brightness matches; three other observers were run on a subset with consistent results. The luminance profiles of the outer background B, the inner backgrounds S_1 and S_2, and the test spot T were kept fixed throughout each experimental run. The luminance of the comparison spot C was varied by the observer until a brightness match with T was achieved. The observer adjusted the luminance of C up or down with a keypad connected to the computer, which, in turn, sent the instrument the updated value. When a satisfactory match was achieved, the observer struck a terminator key and the computer logged the final setting. For each set of conditions, three matches were made. The physical contrast of C was calculated from its luminance and the luminance of the background S_2, according to the defining formula for contrast introduced above. The three values of the contrast of C were averaged. S_1 and S_2 were *the same luminance*, L_0, in all runs. A range of backgrounds B was used so as to produce physical contrasts between S_1 and S_2 and B (average contrasts in the case of the ramp) of 0; +0.06, −0.06; +0.12, −0.13; +0.22, −0.26; and +0.35, −0.46. When they were different from zero, the physical contrast of S_1 with B was positive and that of S_2 negative. This means that S_1 appeared brighter than S_2. In this case, the contrast of C (on S_2) needed to be increased to match spot T (on S_1) in brightness. The physical contrast of T with respect to S_1 was fixed at a value of +0.12 in all of these runs (as in Fig. 1).

Corresponding experiments were done with negative contrasts; the direction of the ramp or the polarity of the square wave was changed so that S_1 was now darker than S_2. In the negative-contrast experiments, the test spot T had a fixed contrast of −0.13 with respect to its background S_1. Again, contrast of C was adjusted to match that of T, now that both were negative. The contrast of C had to be more negative than that of T to match it under these conditions.

To estimate the strength of assimilation, we need to know the dependence of the apparent brightness difference between the spots T and C on the apparent brightness difference between their backgrounds S_1 and S_2. The apparent brightness difference between S_1 and S_2 was estimated in the following way. A third circular spot S_3, equal in area to S_1 and S_2, was presented on a background luminance of L_0. S_3 was equally distant from S_1 and S_2 and presented approximately 2° above them. The physical contrast of S_3 was adjusted to match first S_1 and was denoted C_{S_1} (positive). Then it was adjusted to match S_3 with S_2 and the resulting contrast denoted C_{S_2} (negative). The difference $C_{S_1} - C_{S_2}$ is our measure of the brightness difference between S_1 and S_2 induced by the outer background B. We plotted the contrast of the comparison spot, C_C, versus $C_{S_1} - C_{S_2}$, after first subtracting from C_C its baseline value C_{C_0} when $C_{S_1} - C_{S_2} = 0$. For direct comparison of the results on test spots of negative and positive contrast, the absolute values of $C_C - C_{C_0}$ were plotted against the absolute values of $C_{S_1} - C_{S_2}$. Fig. 3 displays our data in this way.

If there were no assimilation in the perception of brightness, the curves in Fig. 3 would be straight horizontal lines. If assimilation were as strong as the visual response to physical contrast, and therefore brightnesses of object and background were completely additive, the curves would be straight lines with unit slope. Neither of these extreme cases describes our findings. In our experiments, brightness assimilation is less than half as strong as the effect of contrast. Thus, the brightness of an object is to a large extent determined by the local physical contrast around its border. However, assimilation is not negligible.

DISCUSSION

The retinex theory of color vision contains an explicit prediction about the relative strengths of the assimilation process and the response to local contrast: it says they are exactly equal (12, 13). Our results indicate that this explicit prediction is not correct quantitatively. However, our experiments have shown that the basic mechanisms postulated in the retinex theory exist and can be measured. A more accurate theory, utilizing our measurements, should have greater predictive power.

It is well-known to retinal physiologists that the retina responds to physical contrast (4, 14). The retina's contrast dependence is mainly a result of the action of localized gain controls in photoreceptors and in the retinal network that rapidly adjust the gain of the retina to be approximately inversely proportional to its recent past level of illumination (4).

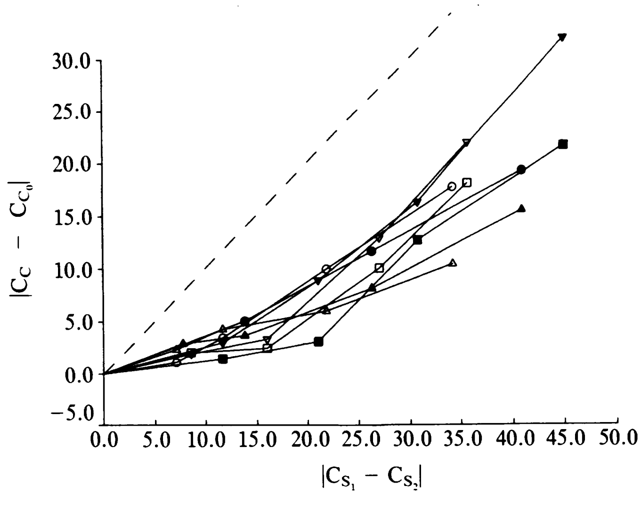

FIG. 3. Experimental measurements of the strength of assimilation for subjects R.C.R. and R.M.S. The abscissa is the apparent brightness difference between the two inner backgrounds, $C_{S_1} - C_{S_2}$, measured by brightness matching with a comparison spot as described in the text. The ordinate is the contrast of the comparison spot minus its baseline value when the outer background had zero contrast, $C_C - C_{C_0}$. ■, R.C.R. ramp; □, R.C.R. square; ●, R.M.S. ramp; ○, R.M.S. square; ▼, R.C.R. negrmp; ▽, R.C.R. negsqr; ▲, R.M.S. negrmp; △, R.M.S. negsqr. "Ramp" values were obtained with the outer background having a ramp luminance profile, as in Figs. 1 *Upper* and 2 *Upper*. "Square" means that the outer background B was a bipartite field as in Figs. 1 *Lower* and 2 *Lower*. "Negrmp" and "negsqr" results were obtained when the contrasts of test and inducing fields were reversed, for ramp and bipartite outer backgrounds, respectively. To compare these negative-contrast results with those obtained with positive contrast, the absolute values of $C_C - C_{C_0}$ were plotted against the absolute values of $C_{S_1} - C_{S_2}$. The slope of the straight line that best fits the data and goes through the origin was 0.45.

If the neural signal from the retina to the brain is only in terms of local contrast, then assimilation must be due to computational activity of the brain acting on the contrast signals it receives from the retina. Another possibility that our present experiments do not rule out is that assimilation is due to the same signals that cause the dependence on contrast. Assimilation does behave functionally like a spatial "spreading" of contrast—for instance, in Fig. 1 from the border between B and S_1 to the border between S_1 and T. It is conceivable that laterally spreading inhibition from the outer background B could have similar effects on spots T and C as it has on annuli S_1 and S_2. However, we believe this explanation is unlikely because of the distance involved, over ½° in the experiments reported here. Moreover, there seem to be significant interindividual differences in the strength of assimilation, whereas the effect of physical contrast is basically similar in the subjects we have seen. Similar observations were reported by Heinemann (1, 2). The nature of the mechanism for assimilation is at present unknown.

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