The influence of depicted illumination on brightness

S. MARK WILLIAMS, ALLISON N. MCCOY, AND DALE PURVES*

Department of Neurobiology, Box 3209, Duke University Medical Center, Durham, NC 27710

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ABSTRACT The striking illusions produced by simultaneous brightness contrast generally are attributed to the center-surround receptive field organization of lower order neurons in the primary visual pathway. Here we show that the apparent brightness of test objects can be either increased or decreased in a predictable manner depending on how light and shadow are portrayed in the scene. This evidence suggests that perceptions of brightness are generated empirically by experience with luminance relationships, an idea whose implications we pursue in the accompanying paper.

The misperception of luminance relationships in the presence of simultaneous contrast is a well known psychophysical phenomenon in which two test regions of the same luminance are seen as having different brightnesses when presented against different backgrounds. Thus, a gray patch on a dark background appears brighter than the same patch on a relatively light background (Fig. 1). The explanation of this effect given in most contemporary texts (e.g., refs. 1–7) is predicated on the opposing center-surround organization of the receptive fields of lower order visual neurons and the lateral inhibitory interactions that this organization entails (8–10). Thus, a misperception of relative brightness is taken to arise because the neurons whose receptive field centers lie just within the diamond on the dark background in Fig. 1 fire at a different rate than the neurons whose receptive field centers lie just within the diamond on the light background.

It has been apparent for more than a century, however, that at least some illusions of brightness do not depend on local contrast (reviewed in refs. 11–13). For example, in the Wertheimer–Benary illusion, two isoluminant gray targets in a black pattern differ in brightness despite the absence of any differences in local contrast (14, 15); and, in the Mach card illusion, the brightnesses of the two faces of a folded card are perceived differently depending on whether the junction of the faces is seen as extending toward or away from the observer (16). More modern investigators also have described perceptual responses to various patterns of luminance that are difficult to explain on the basis of the receptive field properties of lower order visual neurons (17–19). Finally, at least one electrophysiological investigation has failed to find evidence for altered activity of lateral geniculate neurons as a function of the contrast between a test patch and its surround (20). Such stimuli nonetheless affect the responses of cortical neurons, suggesting that the perception of simultaneous contrast is not related directly to the receptive field properties of subcortical neurons (21).

The studies reported here were aimed at evaluating this conflicting evidence in a series of computer-generated scenes in which we systematically could change the apparent illumination of equiluminant test patches while maintaining local contrast relationships. We then measured how these manipulations of the scene affected the perception of relative brightness. As discussed in the accompanying paper, these observations lead to a fundamentally different concept of how perceptions of brightness are generated.

EXPERIMENTAL PROCEDURES

Construction of Graphics and Testing of Perceptual Responses. The graphics used to test the perception of geometrical objects of known luminance in various scenes were created with a Powerwave 604/120 computer (Power Computing, Round Rock, TX), ADOBE ILLUSTRATOR 7.0 and PHOTOSHOP 4.0 (Adobe Systems, Mountain View, CA), and STUDIO PRO 2.0 (Strata, George, UT). All cues about illumination were depicted so as to leave unaffected the contrast between the test diamond and its local surround. The dimensions and gray scale values of the stimulus elements in representative scenes are indicated in Fig. 2A and B.

The images were presented to eight subjects with normal acuity and color vision (the three authors and five naive subjects who were paid for their participation) on a calibrated 48-cm (diagonal) color monitor (Apple Multiple Scan-20; monitor resolution was 1024 × 768; color depth set to 256 grays; scan rate 75 Hz, noninterlaced). The monitor was viewed at a distance of 60 cm in an otherwise darkened room. An interface created in DIRECTOR 6.0 (Macromedia, San Francisco) provided “buttons” under each graphic that allowed the subject to darken or lighten the diamonds and a “match” indicator that recorded the gray scale value of the fully adjusted target (Fig. 2C). When a subject clicked the “lighten button,” the eight-bit gray scale value originally assigned to the test diamond was increased by 3 units (~0.5 candelas/m²); conversely, the “darken button” reduced the...
value by 3 units. Once the target diamond had been adjusted to appear as nearly similar to the other diamond as was deemed possible, the subject designated a match, resetting both target diamonds to their initial equiluminant values and prompting the subject to perform the same task on the other diamond.

Fig. 2. The dimensions (in degrees) of the various stimulus elements and their respective gray scale values (0–255) in the card scene (A; see Fig. 3), and the billboard scene (B; see Fig. 6). Colorized areas indicate regions of the images in which gray scale changes were made to indicate the addition of light or shadow. C shows the matching task that the subjects were asked to perform, the outer border indicating the edge of the computer screen. The “brighten” and “darken” buttons under the graphic on the left allowed subjects to adjust the brightness of the left test diamond until it appeared the same as the right diamond; hitting the match button then recorded the result. The similar buttons on the right subsequently allowed the subject to match the right diamond to left after the test diamonds had been reset to equilumiance.

Fig. 3. Scenes used to evaluate the effect of changing the apparent illumination of the test targets while maintaining the luminance values of both the targets and their surrounds. (A) Test diamonds and surrounds presented such that they appear as intrinsic components of an evenly illuminated card. (B) Test diamonds and surrounds presented such that the left diamond lies in an apparent shadow cast by an object between the light source and the card. (C) Test diamonds and surrounds presented such that the right diamond appears to lie in a specifically lit region, created by an opening that allows light to fall directly only on the right half the card.
match two diamonds of initially different luminance on a neutral background that filled the entire screen. The purpose of the control was to provide a diversionary task between each test and to monitor performance levels during the course of the trials. Finally, the match values were exported to a spreadsheet program for graphical and statistical analysis. All subjects carried out 10 different trials each, during which they judged the relative brightness of 30 matches in the 15 different graphics presented in pseudorandom order (as well as the 15 control matches). The total testing time for each subject was ≈5 hours.

**Relationship of Luminance and Brightness.** Under a given set of conditions, perceived brightness is linearly related to cathode ray tube gray scale values, a fact that we confirmed by direct measurements from the test monitor under the conditions of our trial sessions. The luminance value corresponding to any particular gray scale value can be determined by reference to a standard text (e.g., ref. 22, pp. 415–416). For the sake of simplicity, we have presented the results in terms of the gray scale adjustments made to equalize the perceived brightness of the two test diamonds.

The definition of the word “brightness” also requires some comment. The photometrically determined luminance of an object (that is, the light energy that reaches the eye, corrected for the sensitivity of the human visual system) is dictated by the surface reflectance of the object and the intensity of the illumination falling on it; a further contribution is made by other endogenous properties of the object if it is itself an emitter of light. The observer’s perception of an object’s luminance—i.e., its brightness—is determined by the physiology of the visual system and is therefore subjective. The aspect of brightness inferred to arise from the surface qualities of an object is referred to as its “lightness,” in distinction to the inferred contribution from any endogenous production of light (which, in this context, is often referred to as its “brightness”) (12, 13, 17, 23, 24). In the present study, we use the term “brightness” in its inclusive sense of describing both these contributions to the perception of luminance relationships. Subjects simply were told to adjust the appearance of the test diamonds until they looked as much alike as possible.

**Statistical Comparisons.** The judgments of relative brightness made by the eight subjects as a group are given as means; the significance of the average differences between performances on the various tests of perception are indicated as $P$ values, determined by paired $t$ tests. The complete data set for each subject, showing sampling error and variability across subjects, is presented in the summary tables in the accompanying paper.

**RESULTS**

The Influence of Shadow and Light Depicted by Transparency. We first manipulated a simple scene (Fig. 3) to indicate by the depiction of transparency that the left test diamond and its surround lay in shadow. Changing the depiction from that of an evenly illuminated card where the dark/light contrast border signifies regionally different surface qualities (Fig. 3A) to a scene in which the left diamond and its surround appear to be shadowed (Fig. 3B) enhances the brightness difference between the two test diamonds. Although the diamond in the dark surround in Fig. 3A already appears to be brighter than the equiluminant diamond on the light surround, this effect is increased by the implication of a superimposed shadow on the left side of the card.

To measure the magnitude of this effect, subjects were asked to adjust the brightness of the left (and subsequently the right) target diamonds in the graphic in Fig. 3A until the diamonds in each panel appeared to have the same brightness; the same procedure also was carried out for the graphic shown in Fig. 3B (the order of the presentations and adjustments was randomized within a larger series of 15 graphics and a corresponding number of controls). When the surround of the left diamond was depicted as lying in shadow, the perceived brightness difference between the two test patches was increased by an average of 41% compared with the perceived brightness difference when the surround was depicted as an unshadowed feature of the card (Fig. 4).

Next, we altered the scene by depicting a local source of light rather than shadow, keeping all other luminance relationships constant (Fig. 3C). In this way, the contrast between the two sides of the card was made to appear at least in part the result of local light rather than local shadow. When the context of the right test diamond and its surround was altered in this way, the difference in apparent brightness between the two diamonds again was increased in comparison to the perception in the depiction of an evenly illuminated scene (Fig. 4). The average adjustment required to equalize the appearance of the test diamonds in this circumstance was 21% greater than the adjustment in the absence of cues about local illumination.

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Finally, we tested whether placing the lighter side of the card in shadow (Fig. 5A) or the darker side in the apparent light (Fig. 5B) would diminish rather than enhance the apparent brightness difference elicited by the standard illusion of simultaneous brightness. As shown in Fig. 5, this is indeed what occurs. These observations show that altering the apparent illumination of a scene can—without affecting the local contrast between the target and its surround—increase or decrease the perceived brightness of a standard test patch.

The Effects of an Added Penumbra. The cues about illumination in the preceding scenes are based on transparency. It was therefore of interest to determine whether another indicator of shadow would further influence the apparent brightness of the equiluminant test patches. The additional cue we chose was a penumbra, the hazy border that is to a greater or lesser degree evident at the edges of naturally occurring shadows. The basis of this phenomenon is that the sun and most other sources of light are extended, so that the light rays reaching the shadow-casting object do not arise from a single point. As a result, the edges of shadows are blurred to an extent that depends on the distance of the shadow casting object from the shadowed surface, the clarity of the atmosphere, and a variety of other factors (see ref. 25). Thus penumbras not only help to indicate that a particular luminance profile is a shadow but convey a range of additional information about the illumination of a scene.

Accordingly, we constructed a billboard scene in which the depiction of a shadow was less definitive than in the card scenes. We then could test whether the addition of a penumbra to the putative shadow, by reducing its ambiguity, enhanced the brightness difference between the two test patches. Fig. 6A shows the scene in the absence of any cues to indicate that the dark surround of the left diamond could be a shadow. Fig. 6B implies a possible shadow lying across the left side of a billboard by virtue of a transparency cue similar to that used in Fig. 3B. However, because the transparency cue is coextensive with the edges of the billboard and no shadow-casting object is shown, the putative shadow also could be a surface feature of the sign. In Fig. 6C, a penumbra has been added to the border of the shadow by means of a gaussian blur filter. The graph in Fig. 7 shows that, on average, the presence of the depicted penumbra enhanced the apparent brightness difference of the equiluminant test diamonds by an additional 8% over the effect of the transparency cue alone. (Note also that the effect of transparency in this scene is less effective than in the scene shown in Fig. 3, presumably because other cues such as the presence of the shadow-casting object are missing.)

**Fig. 5.** The effect of placing the lighter side of the card in apparent shadow (top) and the darker side in apparent light (bottom) (i.e., in a manner opposite the depictions in Fig. 3). These results show that the perception of brightness in response to the evenly illuminated card scene (middle) actually can be reduced when the cues about light and shadow are presented in this conflicting manner.

**Fig. 6.** The effect of a penumbra. (A) Scene in which the dark and the light surrounds of the left and right test diamonds are depicted as surface features of the sign. (B) Scene in which a transparent bar extending across a portion of the sign raises the possibility of a shadow. (C) The addition of a penumbra to the putative shadow depicted in B.
DISCUSSION

The results we describe here are difficult to explain on the basis of local contrast effects mediated by the lateral interactions underlying the receptive field properties of lower order visual neurons; indeed, several investigators have, on the basis of other evidence, reached the same conclusion (e.g., refs. 17–19). The ability to increase or decrease the perceived brightness of the test patches in the computer graphics we have used implies that the scene itself determines the brightness of any component patch, much as the perception of color depends on the spectral return of the entire surface being examined (26). In the face of these results, there appear to be two alternative interpretations: Either the lower order lateral interactions leading to the perception of brightness are far more complicated than currently imagined (accounting, as they must, for the influence of the variety of cues in the scene that we have shown to be pertinent), or a quite different mechanism underlies this aspect of perception. In the accompanying paper, we develop additional evidence that a different mechanism is responsible for the perception of brightness.

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