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Perceptual Organization and the Judgment of Brightness

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The perceived brightness of a grey patch depends on the surrounding context. For example, a middle grey patch appears darker when placed on a bright background and brighter when placed on a dark background. Models to explain these effects are usually based on simple low-level mechanisms such as the lateral inhibition that occurs in the retina, whereby cells in one region inhibit cells in adjacent regions. A new set of brightness illusions cannot be explained by such models. In these new illusions the brightness percept is strongly influenced by the perceptual organization of the stimuli. Simple modifi-cations of the stimuli that should have little effect on low-level mechanisms greatly alter the strength of the illusion. These effects may be ascribed to more complex mechanisms occuring later in the visual system.

A gray patch appears brighter when viewed against a dark background, and darker when viewed against a bright background. This effect, known as "simultaneous contrast," is one of many brightness effects that are commonly attributed to simple visual processes, such as the lateral inhibition that occurs in the retina (1), whereby cells in one region inhibit cells in adajent regions. Another class of models, known as retinex models, have been offered to explain the perception of surface colors in terms of the propagation of information about local luminance changes (2). Both kinds of model are founded on low-level processes that involve simple interactions between neighboring neurons. The outputs of such models should be unaffected by a display's higher-level perceptual properties, such as the perceived depth and form. But we have found that a change in perceptual interpretation can have a profound effect on the judgment of brightness.

Following the customary terminology (3), lightness refers to the apparent reflectance of a surface in the scene, whereas brightness refers to the apparent luminance of a patch in the image itself. That is, an observer in a brightness experiment is asked to judge the shade of ink on the page, but not to make any inferences about the surfaces of the objects portrayed. In Fig. 1, patches a and c are obviously brighter than patch b because they are seen to have higher luminance on the page. Patch c also appears lighter than patch b, in that the 3-D physical surface represented by c seems to be painted a lighter shade of gray than b. On the other hand, patches a and b seem to have the same lightness, as they appear to represent surfaces painted the same shade.

Lightness judgments can be influenced by high-level perceptual factors (4,5). Figure 1 makes the point with a simple image: The geometry leads to a 3-D interpretation that causes patch b to match patch a in apparent reflectance (lightness), but not to match patch c, which has the same luminance as patch a. Lightness can also be affected by the perception of surface curvature (6). These various lightness phenomena cannot be explained by low-level models. Because an observer in a lightness experiment is judging properties of the objects portrayed, rather than merely estimating the brightness of the ink on the page, one might not be surprised to find that low-level mechanisms fail to explain the results.

In our experiments we used simple stimuli displayed on a computer screen, and used the more "sensory" brightness judgment rather

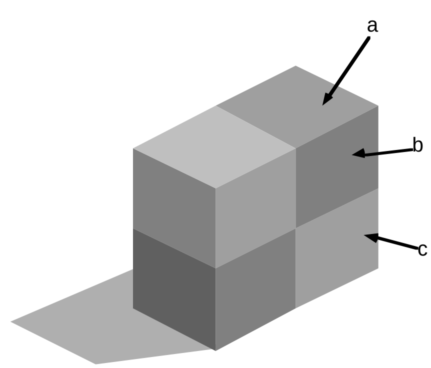

Fig. 1. Distinction between lightness and brightness. Patch c is both lighter and brighter than b. Lightness refers to apparent reflectance of a perceived surface; brightness refers to the apparent luminance of a patch in an image.

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than the more "perceptual" lightness judgment. Thus both the stimuli and the task should have favored the success of low-level models. Nonetheless, the low-level models failed.

The "wall-of-blocks" pattern (Fig. 2A) is built from the two square tiles shown above it. Diamond a_1 looks darker than diamond a_2 although it is actually the same. One might propose that this is an ordinary simultaneous contrast effect, since the region surrounding a_1 is of higher mean luminance than the region surrounding a_2. A modified pattern (Fig. 2B) was used to test this proposition. This pattern is made of tiles containing the same grey shades as before but with a hexagonal shape. The grey shades and the adjacency relationships remain exactly as before. The new pattern differs only in that the straight horizontal strips of Fig. 2A are now bent into zig-zags. The illusion is singificantly reduced; b_1 and b_2 appear almost the same.

To quantify the brightness illusions we asked subjects to perform a nulling task. They adjusted the luminance of the diamonds in the middle row to cancel the illusion and attain a subjective match with the diamonds in the top and bottom rows. The pattern was presented for 0.5s, and the subjects adjusted the luminance up or down after each trial. The brief presentation was used to prevent extended scrutiny of the patterns. The images were shown on a Macintosh II computer equipped with a calibrated Sony Trinitron monitor and an eight-bit video card. Six naive subjects participated and made three judgments of each pattern; they were told to judge brightness of the patches on the screen and not to judge the lightness of the 3-D surfaces portrayed.

The top and bottom rows of diamonds had a luminance of 10.7 mL. For Fig, 2A the perceived match occured when the center row had a luminance of 7.9 mL, that is, when the rows were in a 1.35 to 1 ratio, for a 35% effect. For Fig. 2B, the match occured at 9.7 mL, or a 1.10 to 1 ratio, for a 10% effect. If we take the ratios as a nominal measure of illusion strength, we can say that the brightness illusion in Fig. 2A was over three times as large as that in Fig. 2B.

Figure 2A is seen as a wall of cubical blocks viewed through light and dark horizontal strips, as if there were light and dark transparent filters interposed between the observer and the blocks. The luminance may be perceptually divided between the strips and the blocks (7), so that a diamond of a given luminance can be seen either as a dark diamond behind a light strip or a light diamond behind a dark strip. The perceptual inferences apparently influence the brightness judgments. In Fig. 2B, there is no impression of transparency and thus only a small residual brightness illusion, which might be attributed to low-level processes such as those underlying standard simultaneous contrast effects.

It is plausible that the configurations of

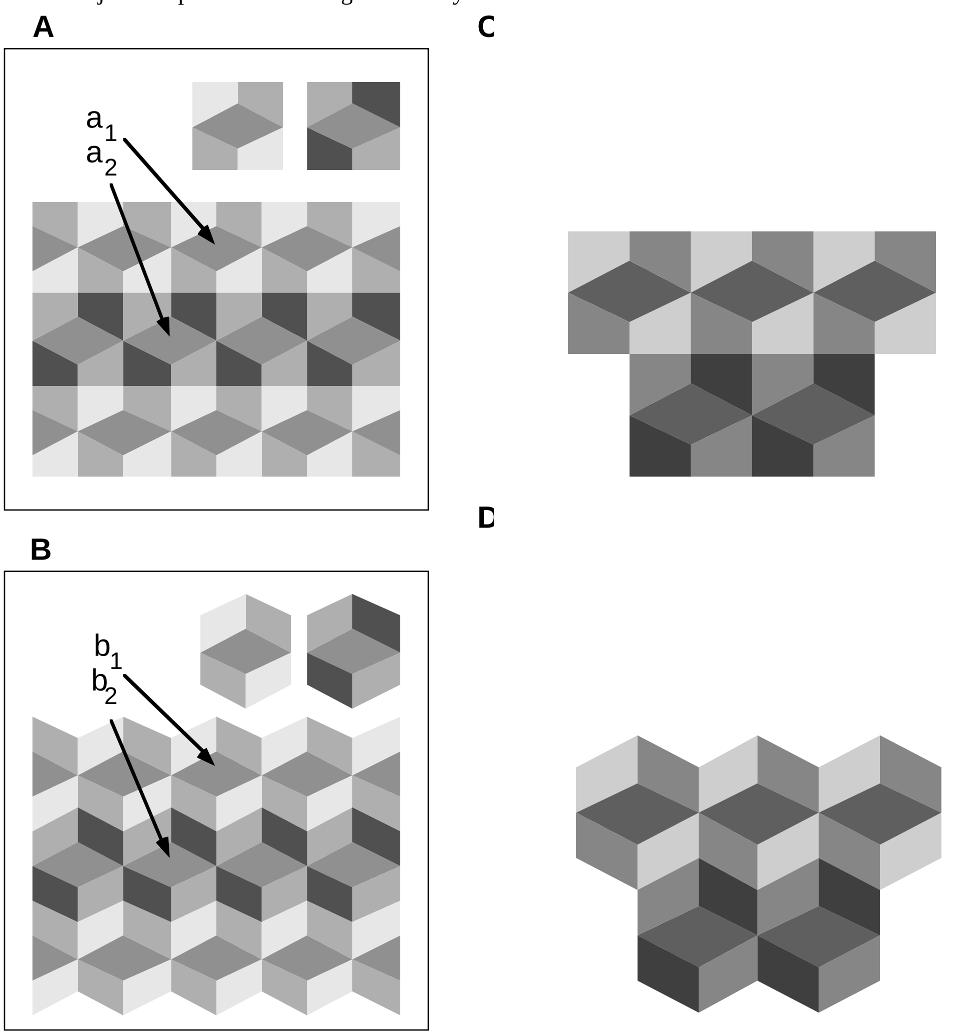

Fig. 2. Effects of perceived transparency on brightness judgements. (**A**) A pattern made by repeating two square tiles. A brightness illusion results: The diamonds a_1 and a_2 are the same shade of gray but appear quite different. (**B**) Pattern generated with hexagonal tiles with the same shades of gray as the pattern in (A), producing the same edge relationship but a reduced brightness illusion. (**C** and **D**) The junction types found in the two figures.

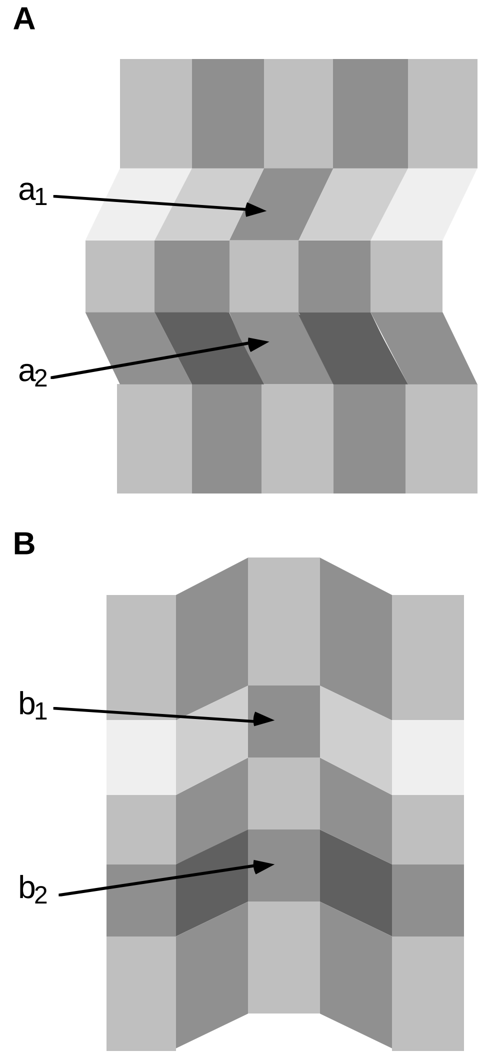

Fig. 3. Effects of perceived shading on bright-ness judgments. (**A**) The patches a_1 and a_2 are thesame shade of gray, but a_1 appears much darker than a_2. (**B**) Pattern made of patches with the same gray shades as in (A) but with different geometry, leading to a different interpretation and reduced brightnes sillusion.

grey-level junctions are critical for the determination of the perceptual organization and thereby the lightness and brightness percepts. When the X junctions of Fig. 2A (marked c_1 in Fig. 2C) are bent into the Ψ junctions of Fig. 2B (marked d_1 in Fig. 2D), a new set of constraints are imposed, leading to a new interpretation. Thus one promising class of models for this reorganization would involve the propagation of constraints from gray-level junctions.

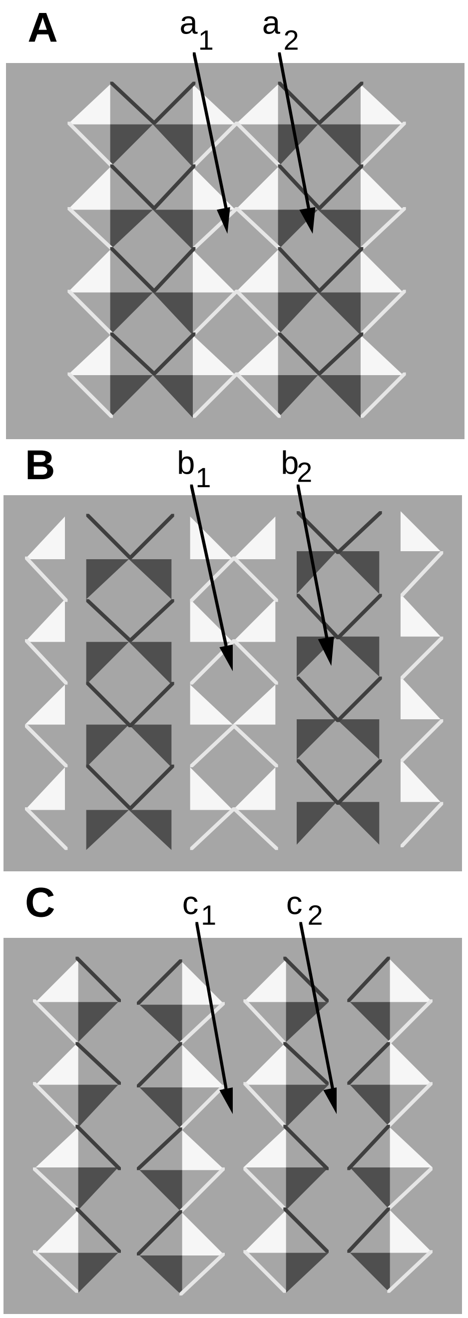

Fig. 4. Variants of the argyle illusion. (**A**) The basic pattern for generating the illusion. (**B**) The same pattern as (A) with the inducing elements spread apart so as to destroy the sense of transparency. The illusion is reduced. (**C**) The same pattern with the inducing elements spread apart so as to retain the sense of transparency. The illusion remains.

A second example is shown in the "corrugated plaid" pattern (Fig. 3). Each figure is derived from the same 5 by 5 matrix of gray levels in the same orientation. That is, the upper left patch is the same gray shade for each, and so on, in raster sequence. (Note the images are not rotated versions of each other.) The only difference is in the shapes of the patches. The grey levels and the edge adjacency relationships are identical in the two figures.

A strong brightness illusion is produced in Fig. 3A: Patch a_1 appears much darker than a_2 even though it is in fact the same. On the other hand, Fig. 3B displays only a weak brightness illusion: Ppatch b_1 appears only slightly darker than b_2. The nulling task verified this effect: When a_2 had a luminance of 8.1 mL, a_1 was judged to match when its luminance was 13.8 mL, for a 70% effect; but b_1 was judged to match b_2 when its luminance was 9.7, for a 20% effect. As before, the effect was over three times as large in the first condition as in the second. Thus, a seemingly modest change in the geometry substantially altered the brightness illusion.

Figure 3A is seen as a 3-D object, with different amounts of illumination falling on the different planes. Under this interpretation a_1 is a dark gray patch that is brightly lit, while a_2 is a light grey patch that is dimly lit. The fact that the brightness is changed suggests again that the inferred reflectance influences the brightness estimate. The situation is different in Fig. 3B. The two patches are perceived as lying in the same plane with the same illumination; thus, their inferred reflectances should be the same. The small residual brightness illusion might be attributed to low-level processes.

Another effect may be called the "argyle illusion" (Fig. 4A). The two diamonds, a_1 and a_2, each consist of the same shade of grey (which is also the same shade as the background). These patches are judged to have very different brightnesses. When viewed on a monitor, the effect is so compelling that many experienced observers refuse to believe the display is correct. In this stimulus there is a sense of light and dark strips overlying the columns; the strips might be seen, for example, as transparent filters of light and dark shades. Subjects report that the diamonds that seem covered by a light filter appear darker, and those that seem covered by a dark filter appear brighter. For Fig. 4A the diamonds appeared to be of the same brightness (8) when the luminance of the diamonds in the two columns were 8.2 mL and 13.0 mL, for a 59% effect. Again, we may suppose that the inferred reflectance of the patch is altered by the process of discounting an overlying filter and that this influences the brightness judgment.

The sense of transparency is destroyed if the inducing elements are spread apart (Fig. 4B). The illusion is substantially reduced: The diamonds b_1 and b_2 were judged to match when their luminances were 9.8 mL and 11.3 mL respectively, for a 15% effect. The illusion strength is reduced to less than one third of its original size.

The inducing elements can also be spread apart in such a way that the impression of transparency is retained (Fig. 4C). In this case the regions marked c_1 and c_2 appear to have significantly different brightnesses, in spite of the fact that they are part of a continuously connected region of constant luminance. The sense of transparency tends to be reinforced by the X junctions, which are maintained in Fig. 4,A and C, but disrupted in Fig. 4B.

All of the phenomena discussed above lead to the same conclusion: Brightness judgments cannot be simply explained with low-level mechanisms. Geometrical changes that should be inconsequential for low-level mechanisms can cause dramatic changes in the brightness report. It is as if the visual system automatically estimates the reflectances of surfaces in the world, and the resulting lightness percepts inevitably sway the judgment of brightness. Constraints from junctions may be important in determining the perceptual organization that underlies these effects. If a model is to predict the brightness phenomena, it may need to use sophisticated mechanisms that decompose the image into a set of intrinsic images (9) representing reflectance, illumination, and transparency (10).

REFERENCES AND NOTES

1. T. N. Cornsweet, *Visual Perception* (Academic Press, New York, 1970).
2. E. H. Land and J. J. McCann, *J. Opt. Soc. Am.* **61**, 1 (1971); B. K. P Horn, *Comp. Graph. Image Proc.* **3**, 277 (1974).
3. R. Evans, *An Introduction to Color* (Wiley, New York, 1948); L. Arend and R. Goldstein, *J. Opt. Soc. Am. A* **4**, 2281 (1987).
4. A. L. Gilchrist, *Science* **195**, 185 (1977).
5. ____, S. Delman, A. Jacobsen, *Percept Pyschophs.* **33**, 425 (1983).
6. D. Knill and D. Kersten, *Nature*, **351**, 228 (1991).
7. F. Metelli, *Sci. Am.* **230** (no. 4), 91 (1974).
8. In the case of the argyle illusion, subjects were never entirely satisfied with the null match. There was always a residual difference in the quality of the grays, regardless of luminance; this quality was difficult to describe but was invariably noticed.
9. H. G. Barrow and J. M. Tenenbaum, in *Computer Vision Systems*, A. R. Hanson and E. M. Riseman, Eds. (Academic Press, New York, 1978), pp. 3-26.
10. D. Kersten, in *Computational Models of Visual Processing*, M. Landy and J. Movshon, Eds. (MIT Press, Cambridge, MA, 1991); E. H. Adelson and A. P. Pentland, in *Channels in the Visual Nervous System: Neuropyhsiology, Psychophysics, and Models*, B. Blum, Ed. (Freund, London, 1991), pp. 195-207; P. Sinha and E. Adelson, in *Proceedings of the Fourth International Conference on Computer Vision*, Berlin, May 1993 (IEEE Computer Society Press, Los Alamitos, CA, 1993), pp. 156-163.
11. Supported in part by contracts from Goldstar Co., Ltd., and the Televisionof Tomorrow Program of the Massachusetts Institue of Technology Media Laboratory. D. Hubel suggested the term "argyle illusion."

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