The effects of color on brightness

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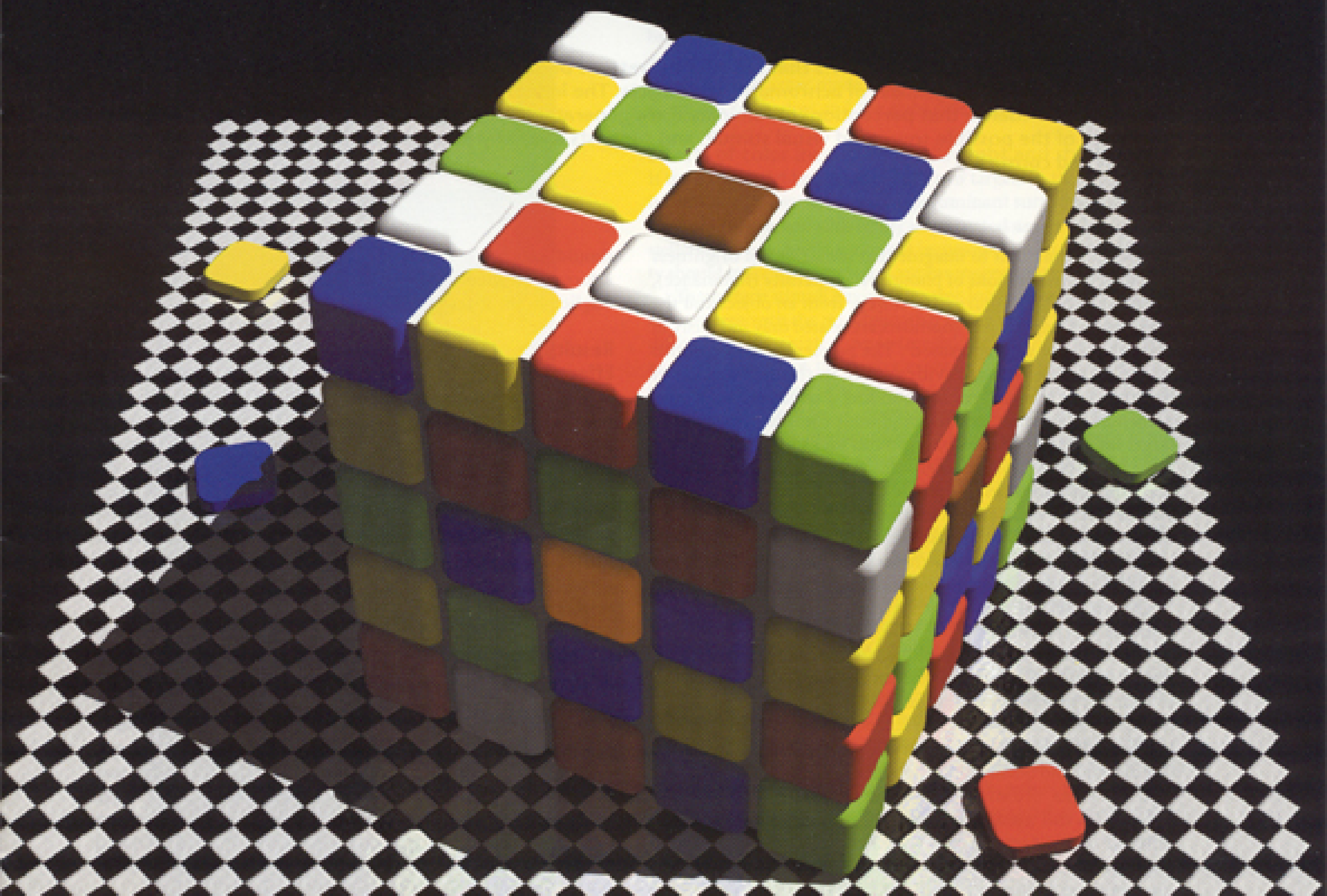

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The effects of color on brightness

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Observation of human subjects shows that the spectral returns of equiluminant colored surrounds govern the apparent brightness of achromatic test targets. The influence of color on brightness provides further evidence that perceptions of luminance are generated according to the empirical frequency of the possible sources of visual stimuli, and suggests a novel way of understanding color contrast and constancy.

Although it is natural to imagine that sensations of brightness are direct representations of photometric intensity (luminance), the amount of light returned to the eye from an object and the experience of brightness it engenders are related only indirectly in a way that is not yet understood[1]. The perplexing nature of this linkage is nowhere more evident than in the dependence of brightness on the surfaces surrounding a target object, a phenomenon called simultaneous brightness contrast. Thus, a gray target on a relatively dark background looks brighter than the same target on a lighter background. As a result of this contextual influence, most psychophysical explanations of brightness assume that the visual system computes this sensation using luminance ratios across the contrast boundaries in a scene[1–3]. In keeping with this interpretation, increasing the number of luminance boundaries surrounding a visual target enhances simultaneous brightness contrast even when the overall luminance of the surround is kept constant[1,4,5].

This consensus notwithstanding, an alternative possibility is that sensations of brightness are not determined by luminance as such, but by information about how the amount of light reaching the eye from the objects in a scene (to which we subsequently refer as the 'stimulus') is most likely to have been generated. The amount and quality of the light returned to the eye are determined by the illumination of the objects in a scene, the reflectances and transmittances of those objects, and the transmittance of the space that intervenes between the objects and the observer. As an observer cannot compute the relative contributions of these factors to a given stimulus by a direct analysis of luminances (because information about these contributions is not present in the stimulus), and as a successful response to the stimulus depends on proper evaluation of these relative contributions, we argue that the visual system must resolve this dilemma by having the stimulus elicit an association (the percept) that accords with what the source of the stimulus has, on average, turned out to be[6–10].

Here we tested the merits of this empirical conception of visual processing by manipulating the colors surrounding an achromatic target. This approach allowed us to examine the effects of changing the probable source of a stimulus without altering its luminance. If computations of luminance ratios across contrast boundaries are the basis of brightness, then manipulating equiluminant colors should have little or no effect. If, however, perceptions of brightness are associations determined by the relative frequency of the possible sources, then manipulating colors should alter brightness according to the empirical (statistical) information about illumination, reflectance and transmittance implicit in the spectral return.

Results

Effects of colors consistent with light and shadow

Subjects were first shown the four scenes in Fig. 1a, which consisted of two differently colored surrounds, each with an identical gray target at the center. The right surround in each scene is ten times more luminant than the left surround; as a result, the central target on the right looks darker than the identical target on the left. To measure this perceptual difference (which cannot be faithfully reproduced in the accompanying figures because of the limitations of color printing), subjects adjusted the luminance of the central gray target on the right until it matched the target on the left.

Subjects next viewed the scene in Fig. 1b, in which the two surrounds comprise 24 differently colored squares instead of a single uniformly colored surface. Since the colors in each array were the same as those used in Fig. 1a, the luminance profile of the multicolored scene in Fig. 1b was identical to the uniformly colored scenes in Fig. 1a. As before, subjects adjusted the target embedded in the more luminant (right) surround until the two targets matched in brightness. In this case, however, the average adjustment required to match the targets was 53% greater than the adjustment required in the scenes with uniformly colored surrounds. Thus, increasing number of equiluminant colors in the two surrounds increased brightness contrast.

The effect on brightness elicited by increasing the number of colors was not simply a consequence of the larger number of distinct surfaces in the stimulus. Thus, when subjects were presented with the same scenes segmented into arrays of 24 distinct tiles (**Figs. 2a** and **b**), the average difference in the adjustments required to match the brightness of the targets were not significantly changed (56%, as compared to 53% in **Fig. 1**). Nor were these results a consequence of a greater number of chromatic boundaries in the stimulus, because spectrally identical scenes can induce different perceptions of target brightness (**Fig. 3**). Thus, when subjects were presented with two multicolored scenes that were spectrally identical but rotated by 180°, the average adjustment required to match the luminance of the achromatic test tiles in the differently oriented scenes was 46% greater for the presentation in Fig. 3a compared to that for Fig. 3b. If the different perceptions of target brightness in Figs. 1 and 2 were

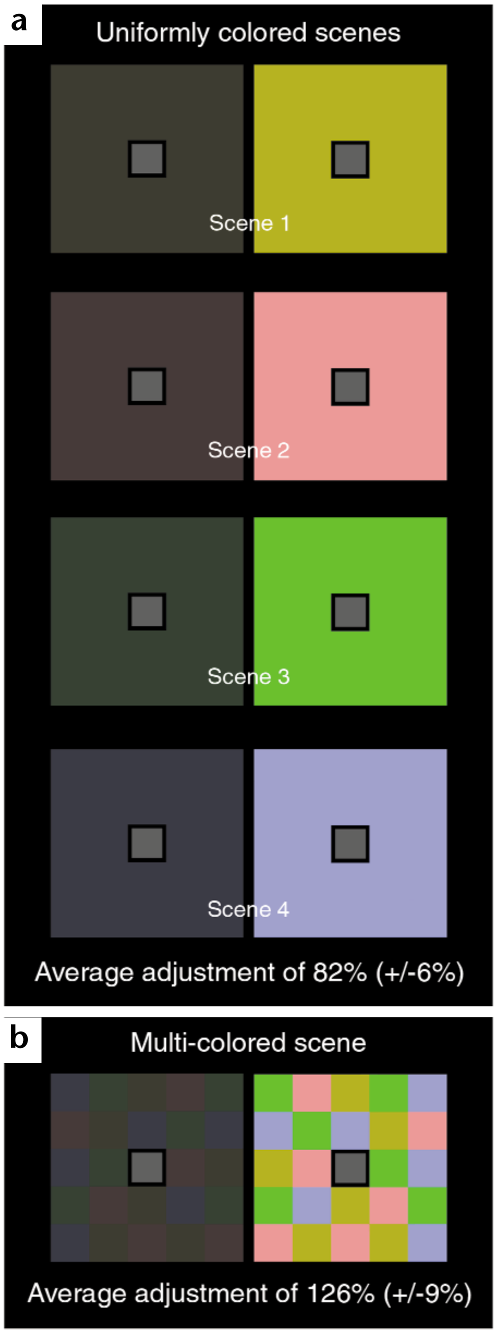


Fig. 1. Effect of increasing color information consistent with a particular condition of illumination on perceived brightness. (**a**) Four scenes consisting of equiluminant gray targets embedded in uniformly colored surrounds that differ in luminance (the surround on the right is in each case 10 times more luminant than the surround on the left). (**b**) A scene in which each of the four equiluminant colors in (**a**) are broken up in patches such that each color is represented six times in the two surrounds. A greater average adjustment was required to make the two targets look the same in the scenes with multiple equiluminant colors in the surrounds than in the scenes with uniformly colored surrounds ($p < 0.001$). (As responses of subjects to the various uniformly colored arrays in (**a**) were not statistically different, data were combined.) Figures only approximate scenes shown to subjects because some of the colors used are outside the printer's gamut; furthermore, effects are weaker than on the computer screen because the combined presentation allows the information in one scene to affect that in the others.

determined by the number of spectral boundaries, then spectrally identical but differently oriented scenes like those in Fig. 3 should induce the same perceptions of target brightness.

The results documented in Figs. 1–3 do not, therefore, support the idea that sensations of relative brightness arise from computations of luminance ratios across contrast boundaries. Nor did the scenes that generated enhanced differences in target brightness vary in perspective, surface curvature or contour junctions, which are other characteristics on which such computations might be based[11–14]. It is apparent, however, that the brightness difference of the two achromatic targets was always enhanced when the information provided by the equiluminant colors in each array made it more likely that the left side of the scene was in shadow and the right side in light.

Effects of color inconsistent with light and shadow

If the differential brightness of the two targets in these figures is increased by a constellation of equiluminant surrounding colors consistent with two differently illuminated arrays, then a constellation of equiluminant colors inconsistent with this possibility should make the two targets appear more similar in brightness.

To produce stimuli having the same luminances and hues but inconsistent with the possibility that two sides of these scenes are differently illuminated, we increased the saturation of the red and blue squares in the darker array in Fig. 2b while maintaining their luminance. The rationale for this approach was that a stimulus perceived to be more saturated is likely to have arisen from a well illuminated surface, whereas an equiluminant stimulus perceived to be less saturated is more likely to have arisen from a less well illuminated surface (because, if the amount of light coming from two surfaces is the same, the surface reflecting a narrower range of wavelengths, and thus perceived as more saturated, will typically have been under stronger illumination). We therefore presented subjects with a scene similar to that in Fig. 2b, but in which the saturation of the red and blue tiles in the less luminant (left) array was greater than the corresponding array in Fig. 2b (**Fig. 4a** and **b**).

Under these conditions, the adjustment required to match the target squares in Fig. 4a was much less than the adjustment needed in Fig. 4b. Although it is difficult to explain this result in terms of luminances or luminance ratios, from an empirical perspective, the greater saturation of red and blue tiles in the left array in Fig. 4a makes it less likely that this part of the scene lies in shadow than the left array in Fig. 4b (which has exactly the same luminance profile).

Relationship to brightness constancy

These observations on brightness contrast bear equally on the phenomenon of brightness constancy, in which different luminances induced similar perceptions (instead of the other way around). Two target squares that differ fourfold in luminance (**Fig. 5a**) have been placed on the surfaces of a multicolored cube (**Fig. 5b**; the targets are colored here to help distinguish them from the surrounds). Despite the fourfold difference in luminance, the two targets appear similarly bright. This striking percept suggests that constancy arises in this instance because the concordant information provided by the 24 distinct, equiluminant tiles on surfaces of the cube in Fig. 5b enhances the probability that the surfaces have similar reflectances, but are differently illuminated. In support of this hypothesis (and consistent with the observations in **Figs. 1–4**), constancy begins to fail when the colored tiles surrounding the targets are replaced with gray surrounds that have the same luminances as the corresponding sides of the cube in Fig. 5b (**Fig. 5c**). This effect is even more striking if the relevant surfaces are depicted so as to leave uncertain their arrangement in space, which further decreases the probability that the surfaces are differently illuminated (**Fig. 5d**). In short, contrast and constancy are not fundamentally different perceptual phenomena, but superficially different manifestations of the same empirical process.

Discussion

The perception of visual targets clearly depends on their context. But how the surroundings of an object influence its perception has been much debated. As noted, explanations of simultaneous brightness contrast are generally predicated on the computation of luminance ratios across contrast boundaries, the enhancement of this effect by an increased number of different surfaces being attributed to the greater number of contrast boundaries in the scene[1–4]. As we have shown, however, the same enhancement can be elicited by surrounding the test targets with surfaces made up of multiple equiluminant colors. Whereas the color in these scenes increased the number of distinct surfaces by virtue of spectral differences, the luminance of the stimulus and number of luminance boundaries remained the same. How, then, can this and the other effects of color on brightness that we describe be rationalized?

The explanation implied by all these observations is that empirical information provided by color changes the relative probability of the possible sources underlying the stimuli, thus changing the perception of brightness. In Fig. 2a, for example, only a single spectral quality is available to indicate the provenance of the light; with this limited information, the relative contributions of reflectivity, illumination and transmittance to the light coming from the various components of the scene remain highly uncertain. When, however, a number of different spectral returns are present in the stimulus as in Fig. 2b and, moreover, are all consistent with a particular stimulus source (two differently luminant regions arising from differences in their lighting), this ambiguity is reduced. As a result, the perceived brightness of the identical achromatic targets embedded in the surrounds is changed in accordance with the increased probability that the targets are differently reflective objects in light or shadow.

By the same token, since illumination usually comes from above, when a pair of multicolored arrays is depicted such that the less luminant array lies above the more luminant one (**Fig. 3a**), the stimulus is consistent with a shadowed surface lying above a similarly colored surface in direct light. When, on the other hand, the same stimulus is rotated 180° (**Fig. 3b**), this likelihood is reduced; the scene in Fig. 3b is therefore more consistent with the upper and lower arrays being equally illuminated. As a result, the brightness difference of the two targets in these rotated but otherwise identical scenes is not the same.

In Fig. 4, the difference in target brightness can be similarly explained in terms of the empirical significance of saturated and unsaturated colors. Increasing the saturation of some of the squares in the darker array increases the likelihood that the surface is more reflective and/or more intensely illuminated (see above). Thus this change diminishes the likelihood that the array on the left is in shadow, thereby decreasing the difference in apparent brightness of the two targets. The empirical significance of differently saturated colors also provides an explanation of the so-called Helmholtz-Kohlrausch effect, which refers to the fact that more saturated colors appear brighter at equiluminance than less saturated colors[15,16].

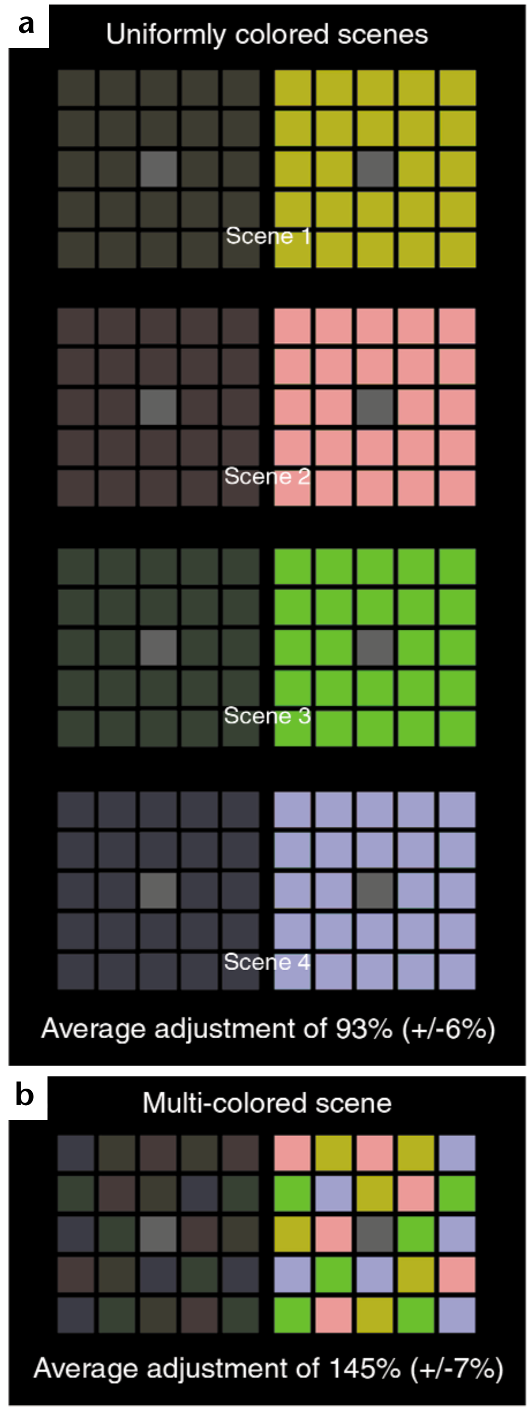


Fig. 2. Effect of multiple colors on the relative brightness of equiluminant targets is not due to the number of distinct surfaces in the scene. (**a**) The same scenes as Fig. 1a, with the uniform surrounds now partioned into 24 distinct surfaces. (**b**) The same scene as Fig. 1b, similarly partioned into distinct surfaces. Despite this partioning, the difference in the average adjustment between the single and multicolor arrays was the same as in Fig. 1. (As there was no statistical difference in the responses of subjects to the different colors in **a**, these data have again been combined.) Thus, the greater difference in the target brightnesses in Figs. 1b compared to Fig. 1a is not simply the result of an increased number of discrete surfaces in the surround. For the reasons given in Fig. 1, the effects are weaker in the figure than in the scenes presented on the computer screen.

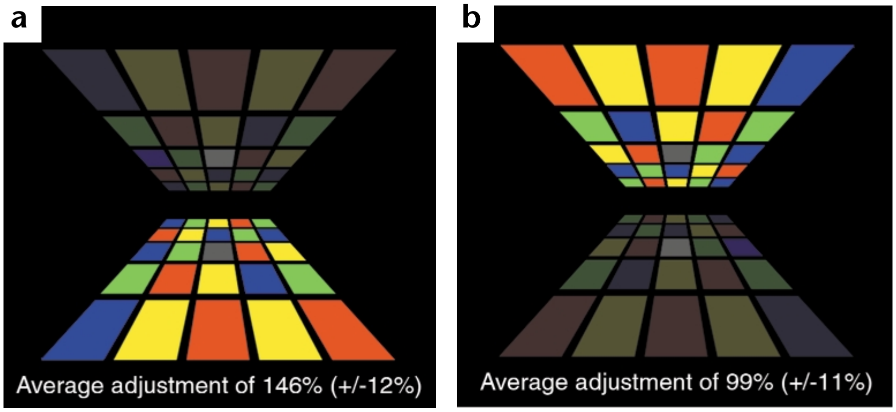
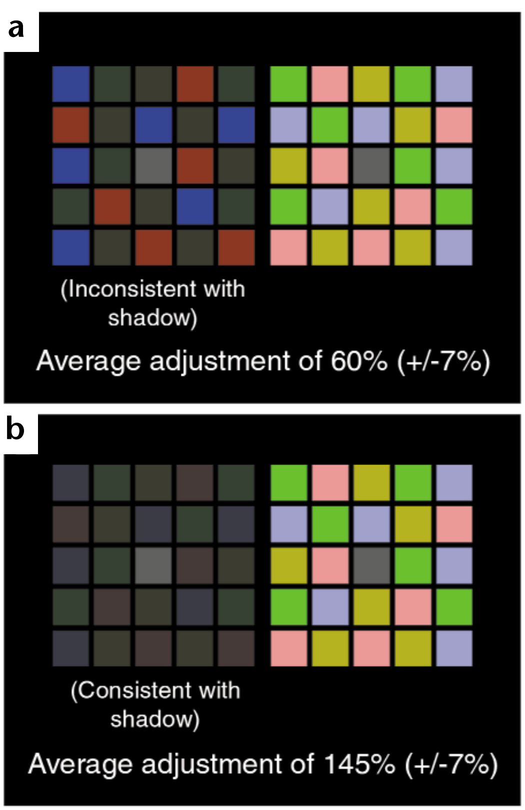


Fig. 3. Effect of spectrally identical scenes on brightness perception. Because illumination is assumed to come from above, the spectral returns in the scene in (**a**) are consistent with the lower array being in light and the upper array being in shadow. However, when the same stimulus is rotated, as in (**b**), it becomes less consistent with this possibility. As a consequence, the identical gray targets at the center of the lighter and darker arrays were perceived to differ more in brightness in (**a**) than in (**b**), as indicated by the adjustments subjects made to equalize their appearance ($p < 0.001$).

Finally, Fig. 5 makes the important point that this empirical explanation of brightness contrast works equally well to explain brightness constancy, which is simply another manifestation of the same probabilistic process that generates color percepts (see also ref. 5).

In neural terms, perceptions of brightness (or color) on a wholly empirical basis would require first, that the developing animal be endowed with neural networks intrinsically biased during the course of evolution to elicit appropriate associations in response to spectral stimuli, and second, that the synaptic weightings of such networks continue to be modifiable by feedback from experience during postnatal development (see ref. 17 for review). The instruction for the evolution and developmental modification of the relevant visual circuitry presumably stems from the success or failure of visually guided behavior in response to the perception of visual stimuli (by natural selection in phylogeny, and by the feedback of neural activity on the formation and maintenance of synaptic connections in ontogeny).



Conclusions

These results indicate that the perceived brightness of any light returned to the eye is a manifestation of its most likely provenance, rather than its photometric value relative to the luminances of other elements in the scene. Evidently, these and presumably all other visual percepts are determined by the gamut of information—including color—relevant to the probable contributions of illumination, reflectance and transmittance to the stimulus. Because different spectral returns convey, in their own right, empirical information about these relative contributions, an important corollary is that the perception of color is itself a manifestation of the empirical significance of a spectral return[18]. Perhaps color contrast and constancy effects, such as those demonstrated by Land[3,19,20], can also be understood empirically in terms of the relative probabilities of the possible sources of such stimuli.

Methods

Construction and presentation of computer graphics. All test graphics were created with a Power Macintosh G3 computer, using Adobe Photoshop 5.0 software and the standard Macintosh color palette. The stimuli were displayed on a calibrated 48 cm (diagonal) color monitor (Sony Multiscan 300sf; monitor resolution, 1024 (768; scan rate, 75 Hz, non-interlaced). The computer interface for each experiment was created with Director 6.0 (Macromedia, San Francisco, California). Subjects with normal acuity and trichromatic vision (the authors and 8 naive volunteers) observed the screen from a distance of 60 cm in an otherwise darkened room after adaptation to the ambient light. The stimuli presented to subjects were specified by the RGB settings of the computer (and were, therefore, device dependent).

Fig. 4. Effect of inconsistent color information on the relative brightness of equiluminant targets. The pair of arrays in (**a**) is the same as that in (**b**; same pair as in **Fig. 2b**); however, the spectral return of the red and blue tiles in the less luminant array on the left has been altered so as to increase the saturation of these tiles while maintaining their luminance. This change caused subjects to make a smaller average adjustment to equalize the appearance of the targets in (**a**) than in (**b**); $p < 0.001$; see text. As in the previous figures, the effects were stronger on the computer screen.

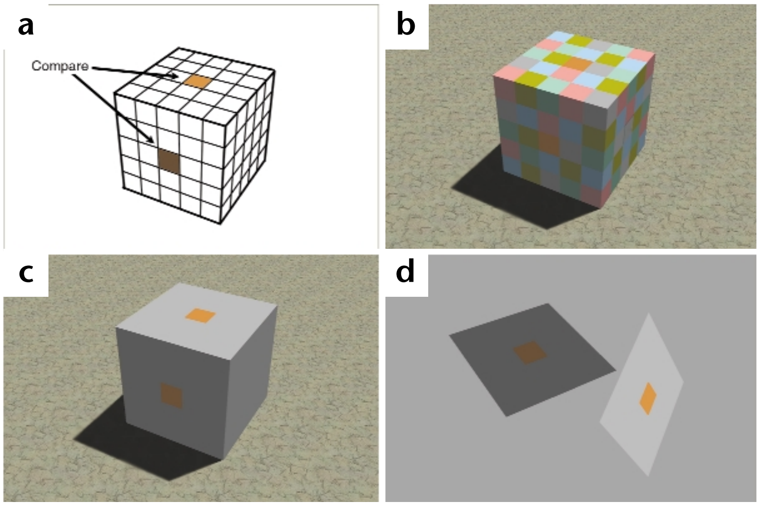


Fig. 5. Relation of these observations on brightness contrast to understanding brightness constancy. (**a**) The colored targets on the upper and lateral surfaces of the cube are identical to the corresponding tiles in the subsequent panels. (**b**) The target tiles in (**a**) have been embedded here in multicolored surfaces, the values of which were precisely chosen to represent the amount of light that would be reflected by two identical surfaces under the implied conditions of illumination. As in previous figures, the tiles in each surround are equiluminant, the overall luminance of the two surrounds differing fourfold. (**c**) The same stimulus as in (**b**), but with the colored targets now in uniform gray surrounds (luminance profiles of scenes **b** and **c** are identical). (**d**) The relevant faces of the cube in (**c**) have been oriented so as to leave their positions in space uncertain. This demonstration shows that the same multicolored surrounds previously used to elicit contrast can, given the appropriate empirical significance, be used equally well to generate constancy.

Testing. Subjects were asked to adjust the radiance of the target in the more luminant (right) surround of the scenes presented until it matched the perceived brightness of the target in the less luminant (left) surround (in these instructions no attempt was made to have the subjects distinguish between 'lightness' (surface appearance) and 'brightness' in the sense of source intensity; thus we have used the term brightness in its general meaning through out this report). The luminance of the colors in the computer-generated scenes was measured photometrically with an optical power meter (Model 371R, Graseby Optronics, Orlando, Florida) under the relevant test conditions. For Figs. 1–4, the luminances of the light and dark surrounds were 55 cd per m^2 and 5 cd per m^2, respectively, and for Fig. 5, 65 cd per m^2 and 12 cd per m^2, respectively. The projected scenes measured 20×9.5 cm on the monitor's screen. Otherwise, these adjustments were made under the same conditions and with the same methods as in our previous studies of brightness[6–10]. Subjects repeated each experiment three times on three separate occasions; average responses for all trials, plus or minus the standard error, are presented; statements of significance are based on Student's *t*-test.

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