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Research Focus

New dimensions in color perception

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Colors are generally ordered in three dimensions, with hue and saturation as polar coordinates of a color circle, and brightness as the third dimension. Intuitively, lines of constant hue (but variable saturation) in such a color space should converge on an achromatic point devoid of hue. However, in new experiments by Ekroll *et al.* using colored patches in colored surrounds, constant hue lines converge not on 'gray' but on the surround color. This paradoxical observation suggests that the standard three-dimensional conception of perceived color is inadequate.

Colors exist in infinite variety, but they can be ordered. In the standard account, each color can be assigned a position in a three-dimensional space where one dimension represents brightness and the other two can be specified by hue and saturation, the polar coordinates of the color circle. This standard model owes its plausibility and its ascendancy to well-documented facts of color mixture. Normal human color vision is 'trichromatic': just three primaries span the space of all colors. Thus, faultless whites and yellows can be formed by mixtures of light from the microscopic red, green and blue phosphor dots of a television CRT screen, even though a white light can have an almost flat spectral energy distribution, very different from the three-primary mixture that is subjectively identical to it. The subjective identity of physically different lights in a trichromatic color match originates from an identity in their neural effects. With just three types of cone photoreceptor cell (roughly speaking, 'red-, green-, and blue-sensitive' cones; they are in fact sensitive to the physical parameter of wavelength), the retina forms a three-dimensional representation of color at any point in the field of view.

Context matters

But color perception is not determined simply by the local stimulus. Contrast with the surround also has a profound influence, as illustrated in Fig. 1. The two thin rings are physically identical purples, but it is the difference of each ring from its immediate surround, rather than the stimulation coming from the ring itself, that determines its appearance.

The convergence paradox

In a careful study of how colors appear when presented in colored surrounds, Ekroll *et al.* [1] have now uncovered a thought-provoking paradox, which they resolve by suggesting that in these situations, phenomenal color space is more than three-dimensional. Loci of constant hue can be determined experimentally for any chosen perceived hue (for instance, for subjectively pure yellow). Given a highly saturated yellow color sample as a reference, an observer can select less saturated samples that match its hue, and these would be assigned to the same constant-hue locus as the reference. When the surround is black, the loci of constant hue (and constant luminance, but variable saturation) form roughly straight lines that radiate from an achromatic (subjectively neutral) point in the constant luminance plane. But Ekroll *et al.* find that if the surround is colored, the experimentally determined loci of constant hue radiate not from the achromatic point but from the *surround* color, heading straight past the subjectively 'achromatic' point as they converge toward the surround! This is a paradox because at the same time, the surround itself, on which all the constant hue lines converge, is seen as colored with its own characteristic hue.

Figure 2 gives an impression of the effect. The eight straight spokes shown describe straight lines in color space, radiating from the blue background color against which they appear on the right. On the left, where the surrounding background is black, these bars naturally appear non-uniform in hue along their length, as each bar is shaded to blue at its center. And yet on the right, each of the same bars appears (subject to the vicissitudes of color printing!) roughly uniform in hue (but varying in saturation).

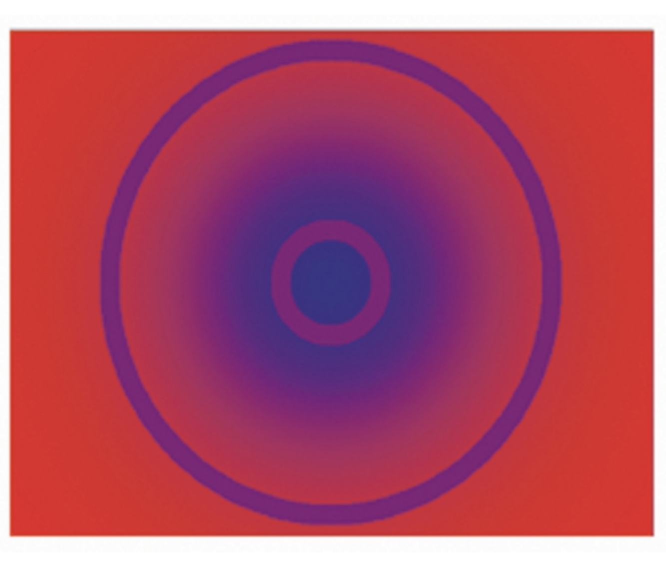

Fig. 1. Color contrast: the inner and outer thin rings are in fact the same physical purple, but the one in the blue surround looks more red and the one in the red surround looks more blue.

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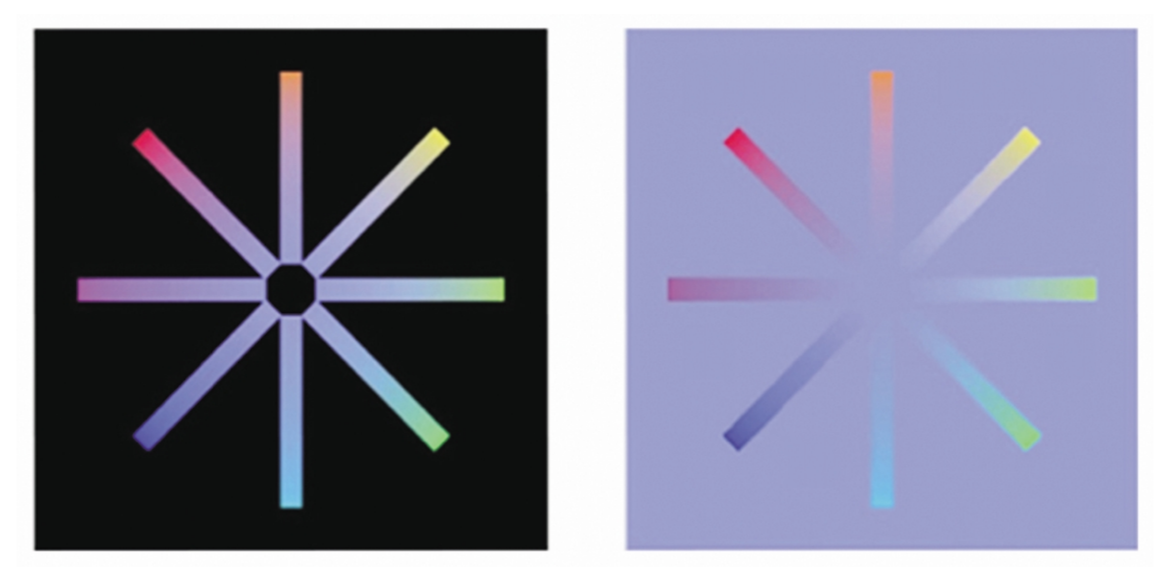

Fig. 2. Left: each of the eight non-uniformly colored spokes is constructed by shading a different hue toward blue. Right: embedding the same eight spokes in a blue surround, however, makes them appear relatively uniform in hue along their length. (Figure kindly supplied by Ekroll, Faul, Niederée and Richter).

In Ekroll *et al.*'s primary experiment, 32 equiluminous colored patches are presented on a computer monitor in two concentric circles, so as to form 16 radially aligned pairs, all within an equiluminous surround. The patches lie correspondingly on two concentric circles in a physically defined color space, with close but easily perceptible spacing. The subject can drag all the color patches around together in color space. When the center is in the red, green or blue corner of the color chart, the display presents an array of diverse reds, greens and blues patches, respectively.

Logic suggests that when the patches are appropriately centered, all hues will be represented in each circle, and radially aligned patches in the inner and outer circles will lie on the same constant hue locus, differing only in saturation. Subjects were asked to search for such a center setting. They could always find one, and Ekroll *et al.* note that when this particular point is reached, 'the otherwise almost uniform collection of colors unfurls rather impressively into a set of colors spanning a full gamut of hues'. The surprise is that this center point is simply the surround itself. Yet each colored surround naturally has its own characteristic hue; and when patches are presented in a colored surround, the patch that is selected as subjectively devoid of color is distinctly different both from the surround and from the convergence point determined with that surround. Paradoxically, this 'achromatic' patch lies along the constant hue locus for colors approximately complementary to the surround.

Resolving the paradox

How can a vividly red surround color provide the origin for a locus of pure yellows, none of them reddish? And how can a given colored patch simultaneously appear absolutely devoid of color, yet share the hue of the complement of the surround? In their explanation of this paradox, Ekroll *et al.* point out that color impressions have a dual aspect. The colored surround imparts an overall 'cast' to the display that influences the selection of an absolutely achromatic color. Indeed, no patch appears truly and completely achromatic in a colored surround: rather, the chromatic cast due to the surround must be balanced by a complementary tint of the test patch. At the same time, the hue of the small patch is determined not by absolute stimulus values but only by the difference (contrast) between the test patch and the surround, as if the color of the surround were being completely *discounted* in judging the hue of the patch – a discounting also implied by the contrast illusion of Fig. 1 [2–5].

Beyond trichromacy

Natural scenes also exhibit this postulated dual aspect of color impressions. When lights are presented in differently colored surrounds, the different contexts can create irreducible differences in the appearance of the reference and comparison fields themselves [6–8]. A white paper in a candlelit scene still appears 'white' (that is, it exhibits 'color constancy'), yet it looks very different from the same paper under the noonday sun, because of the yellowish cast associated with candlelight. Thus, a full spatial representation of experienced color would require not only three dimensions for the color and lightness of the surface itself, but (at least) a further three dimensions representing the perceived brightness and color of the illumination that is cast on the surface.

These phenomena arise not only when viewing objects under chromatically tinted illumination [8,9] but also in seeing through a bluish haze [10,11] or through a partially reflecting transparent surface [12,13]. Analogously, in the domain of achromatic intensity, surface quality ('lightness') has a perceptual reality independent of the cast imparted by the illumination and viewing conditions (which is reflected more in judgments of 'brightness'). Perceived surface lightness, like hue, is largely dependent on contrast with the surround, whereas perceived 'brightness', like the achromatic point, is less so [14].

Implications for a neural mechanism

These phenomenological subtleties are quite consistent with what we know about the neural representation of color. The signal that arrives from the retina is mainly determined not by the local light stimulus, but by the local contrast between a stimulus and its immediate surround [15,16]. This could be invoked as a basis for the constant hue loci (as well as for the illusion of Fig. 1). Such a neural representation captures the differences between different surfaces, but indicates nothing directly about the viewing conditions, such as the overall cast of illumination. The processes by which illumination and other parameters of the viewing conditions are reinstated in perception are not yet well elucidated, but it makes sense that these should require more integration with context than does perception of surface quality. And of course the brain has enough signals to support color experience of a dimensionality far higher than three. This is no heretical departure from the trichromatic theory: all that is necessary is that the signals underlying such perceptual dimensions combine information from different points in the visual field – and indeed the retinal 'local contrast' signals already do this.

To understand how the local-contrast signals within the image are integrated in perception is a problem that neurophysiologists are only beginning to address, although it is already clear that long-range interactions do occur, in primary visual cortex [17,18] as well as at later stages of processing [19]. The work of Ekroll *et al.* increases the challenge of this problem, by highlighting neglected subtleties in the way that perception of a surface depends on the viewing conditions. Gratifying correspondences have been revealed between neural firing rates and judgments of surface hue [19] and lightness [17] under varying viewing conditions, but a complete account of surface perception will require in addition some representation of the viewing conditions themselves, as well as of material properties such as glossiness [20], which also depend on fairly complex spatial computations.

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