Hue and saturation shifts from spatially induced blackness

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We studied changes in the color appearance of a chromatic stimulus as it underwent simultaneous contrast with a more luminous surround. Three normal trichromats provided color-naming descriptions for a 10 cd/m^2 monochromatic field while a broadband white annulus surround ranged in luminance from 0.2 cd/m^2 to 200 cd/m^2. Descriptions of the chromatic field included Red, Green, Blue, Yellow, White, and Black or their combinations. The naming frequencies for each color/surround were used to calculate measures of similarity among the stimuli. Multidimensional scaling analysis of these subjective similarities resulted in a four-dimensional color space with two chromatic axes, red–green and blue–yellow, and two achromatic axes, revealing separate qualities of blackness/lightness and saturation. Contrast-induced darkening of the chromatic field was found to be accompanied by shifts in both hue and saturation. Hue shifts were similar to the Bezold–Brücke shift; shifts in saturation were also quantified. A stage model is proposed to account for the relationships among blackness induction and the inherent nonlinearities in chromatic and achromatic processing. © 2008 Optical Society of America

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1. INTRODUCTION

If color vision behaved completely linearly, then decreasing the luminance of a colored light would alter only its subjective intensity. In fact the light's hue may also vary: depending on its location within the spectrum, a shift to a longer or shorter wavelength may be required to maintain the same hue. This is the well-established Bezold–Brücke (hereafter BB) hue shift for colors seen in *aperture mode*, i.e., in the absence of spatial context [1,2]. These nonlinearities between input and output are of interest because of the insights they provide into the internal mechanisms of color processing.

Aperture mode contrasts with *surface mode*, where a visual environment, such as a luminous surround, is present, and the colored light appears as a reflected-light stimulus. A sufficiently intense luminous surround creates spatial contrast and induces blackness into the light. It is natural to wonder how far this subjective darkening is equivalent to objective changes in luminance and whether it results in comparable changes in hue. If the BB shift is a high-level effect, arising from a stage in visual processing subsequent to the operations of spatial contrast (and color constancy), one might expect it to be evoked as efficiently by induced blackness as by actual changes in stimulus lightness.

To address this issue empirically, Coren and Keith [3] presented observers with two compound stimuli simultaneously, each consisting of a chromatic center and an achromatic annular surround. One center was objectively more luminous than the other, but subjects could induce darkness into it by increasing the luminance of its annulus until the two centers were matched in apparent lightness. When this match was achieved, the centers were also seen as the same hue, implying that the contrast-induced darkening canceled out the hue shift that would otherwise have affected the more luminous center.

The question can be phrased in another way, by specifying a color appearance—for instance, "unique green" or the binary hue "orange" where yellowness and redness combine in equal proportions—and asking whether the wavelength required to produce it is constant across a range of annulus luminance. This latter form of the question was posed by Fuld and Otto [4], who plotted the loci of unique and binary hues for various combinations of central and annulus luminance. The wavelength required to evoke a given color appearance did indeed depend on surround luminance, but those variations did not follow the particular pattern that characterizes the BB shift. It must be noted, however, that those loci were interpolated between color-naming data collected at only 11 wavelengths across the spectrum, so the accuracy of interpolation is limited by the size of the gaps between wavelengths (50 nm).

In addition to the hue shift, changes in absolute luminance affect the saturation of a stimulus. The "Purdy shift" might be an appropriate label for this effect of luminance on saturation, first reported by Purdy [5], and studied more recently by Valberg *et al.* [6]. As luminance decreases, shorter wavelengths, blue to blue-green (less than 520 nm), become more saturated, i.e., more distinct from white. In contrast, longer wavelengths, especially in the mid-yellow region, lose saturation and become "washed-out" [7,8]. Green and red lights are least affected. This is consistent with Fuld's argument that the contribution of S cones for desaturating a signal is nonlinear [9].

Here we examine hue shifts from induced darkening using the color-naming method, where subjects provide a combination of color terms to describe each stimulus [10]. Two lights have the same subjective hue if they elicit the same ratio of (for example) Red- and Yellow-responses. Thus hue shifts are easily quantified by finding the combination of color terms applied to a given wavelength at some annulus luminance and determining the other wavelength that evokes the same combination at some other luminance (interpolating between wavelengths if necessary). In an application of the same technique, with varying central luminance and no annulus [7], the results indicated a BB hue shift in line with those previously obtained from other methods. Specifically, for lights with a perceptible component of Green, this component became stronger as luminance decreased (i.e., the Blue or Yellow components decreased). For longer-wavelength lights with a component of Red, this similarly became stronger.

In addition to the above method, multidimensional scaling (MDS) is used to clarify possible changes in color appearance by converting color-naming functions into an individual color space by way of interstimulus similarities. The result is a description of each stimulus in terms of spatial coordinates rather than as a color-name combination [8,11].

The present study extended the original version of the color-naming technique [8,10] by allowing Black as well as White responses (as in [4]). When White and Black responses function as mutually exclusive opposite extremes of a bipolar continuum of subjective darkness, they contain information about induced blackness. However, they may also function as labels for the desaturation of the stimulus, together describing the amount of grayness diluting its chromatic content. MDS serves to disentangle these two aspects of achromatic appearance from the data before the question of hue shifts from induced blackness is addressed. There is the added incentive that interactions between induced blackness and *saturation* can be examined, once both aspects have been quantified.

To put it another way, a complete description of achromatic appearance in conditions of spatial contrast requires two dimensions [12,13]. Unfortunately, this is not enough to disambiguate the choice of dimensions. Lie [14] distinguished between the "brightness" and "whiteness" of achromatic color in surface mode. In a similar vein Heggelund [15] argued that Whiteness forms one axis of achromatic appearance, while the opposition between Black and Luminous defines a second, orthogonal axis. Again, "Whiteness" and "Blackness" are separate processes in the hyperspherical model of color discrimination of Izmailov and Sokolov [16]. Most recently, Vladusich *et al.* [17] worked with axes of Brightness and Darkness.

A MDS solution may provide clues for building a stage model of how color information is encoded in the course of cortical processing. In this light, the nonlinearities of color processing (e.g., hue shifts) provide a useful criterion for choosing among these alternative frameworks of axes. A framework is a promising candidate if the axes can be interpreted as neural channels in a stage model, which in turn can accommodate the nonlinearities in a parsimonious way. The study by Shinomori *et al.* [18] has shown how the nonlinear properties of induced blackness provide information for such models. In particular, nonlinearities place constraints on the stage of visual processing where spatial-contrast computations occur.

2. METHOD

A. Subjects

The experiment was carried out at Moscow Lomonosov State University, Russia. Participants were three Russian-speaking women aged 21, 22, and 24 years. They were confirmed as normal trichromats using the Rautian anomaloscope [19].

B. Stimuli

$N=156$ stimuli were presented foveally in Maxwellian view. Each consisted of a monochromatic center of fixed luminance ($L_C=10$ cd/m^2 or 38 Td) subtending 2° and a contrast-inducing annulus with 2° inner and 6° outer diameter. Broadband white light from two KGM-24 tungsten-filament sources (ca. 2850 K) were combined with a photometric cube (see [16], Fig. 1). For the annulus, one beam was filtered with a neutral wedge; for the center, the other beam passed through Zeiss interference filters with 4 to 6 nm half-bandwidth. The central wavelength λ_C ranged across 25 values from 425 to 675 nm, with a 26th center consisting of white neutral-filtered light. Six levels of annulus luminance L_A were tested, ranging across three orders of magnitude: 0.2, 2, 10, 20, 100, and 200 cd/m^2 (or 0.76, 7.6, 38, 76, 380, and 760 Td). Thus values of the annulus/center luminance ratio, used as the parameter in the following analysis, were 0.02, 0.2, 1, 2, 10, 20.

C. Procedure

Each combination of central wavelength and annulus luminance ($26\times6=156$) was presented 20 times over 10 sessions, in pseudorandom order. One second of exposure was followed by 15–20 s of darkness while the observer described the appearance of the center using a variant of the color-naming procedure [4,10,11]. Observers could use the six Russian terms for Red (*krasnyj*), Yellow (*žëltyj*), Green (*zelënyj*), Blue (*sinij*), White (*belyj*), and Black (*čërnyj*): R, Y, G, B, W, and Bk. An additional term for Blue in Russian is *goluboj*, but its denotata relate to lighter and low-saturated blues [20]. One, two, or three terms were permitted for a description in order of decreasing salience (e.g., Green; or Yellow-Red; or Blue-Green-Black).

D. Analysis

A color term scored 10 points if it was used in isolation; two terms received 6 and 4 points in order of salience; three terms received 5, 3, and 2 points. Summed over presentations, points for each color term (ranging in value from 0 to 200) produced the color-naming function [7,10]. Comparing color-naming functions between all possible pairs of observers gave correlations of 0.86, 0.90, and 0.88. We decided that this showed sufficient similarity to combine the observers' responses.

Next, the similarity between any pair of stimuli was quantified as the covariance between the corresponding vectors of color-name values before analysis of the matrix of similarities with Kruskal's algorithm for nonmetric multidimensional scaling [11]. MDS represents stimuli as points in an n-dimensional space, arranged so that interpoint distances reflect interitem similarities. A badness-of-fit function $Stress_1$ quantifies the mismatch between distances and similarities.

It is worth emphasizing that any chromatic and achromatic axes emerging from the MDS analysis have the same units. A difference between two stimuli of some percentage in White-naming makes the same contribution to the dissimilarity between them as the same difference of (say) Red-naming: that is, achromatic and chromatic terms are treated equivalently. In this respect the present procedure differs from the "4+1" hue-scaling procedure [8]. There, subjects first estimate the saturation of each stimulus—explicitly analyzing it into an achromatic and a chromatic component—before characterizing the latter in terms of a combination of chromatic terms. There is no guarantee that the achromatic component uses the same units as any chromatic axes.

3. RESULTS

A. Color-naming functions

Figure 1 displays the color-naming functions, i.e., the aggregate score for each of the six color terms, as a function of λ_C, for each of the six L_A.

Figure 1 shows that a sufficiently dim annulus (low L_A) induces W-naming responses, which decrease with increasing L_A. These indicate desaturation of the center (see [21,22]). In the limiting case of $L_A=0$, i.e., aperture mode, Boynton observed that "[w]hen viewing monochromatic aperture colors, one is impressed with how relatively desaturated they appear…" ([23], p. 343). At the other extreme, a sufficiently high L_A again desaturates the central appearance, though in this case by inducing

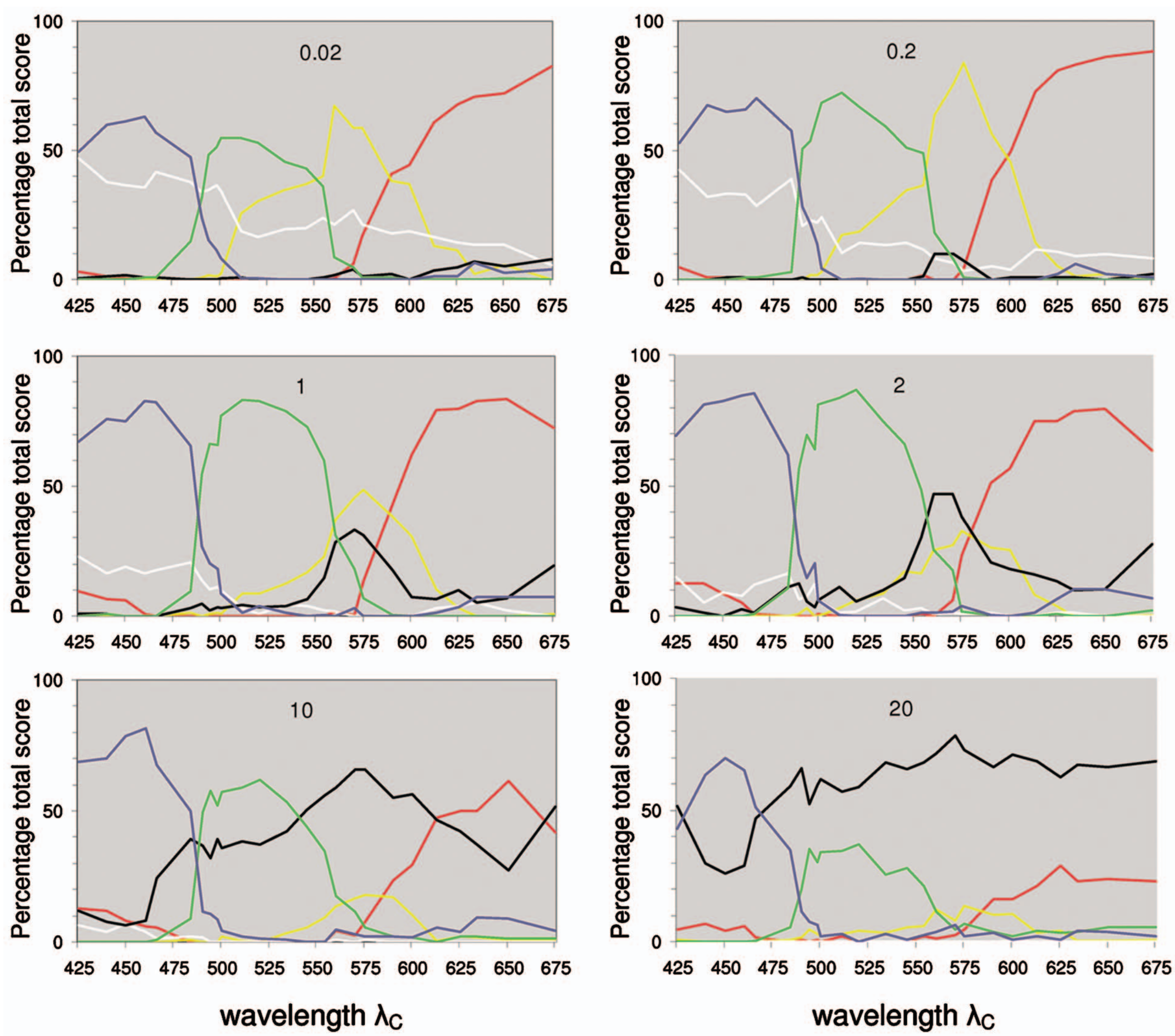

Fig. 1. Color-naming functions, aggregated over three subjects, for six luminance ratios L_A:L_C (where central luminance $L_C=10$ cd/m^2). In each panel, abscissa is wavelength λ_C of the chromatic central field and ordinate is percentage of total naming score. Naming functions are plotted in lines of appropriate color.

Bk-naming. Thus the proportion of chromatic responses is highest at some intermediate luminance ratio L_A/L_C. This ratio is not constant across the spectrum but rather is a function of the central hue. For instance, the Y-naming function peaks around $L_A/L_C=0.2$ (Fig. 1); as L_A increases above this ratio, mid-wavelength yellow lights (around 575 nm) are increasingly named Bk. At longer and shorter wavelengths respectively, R- and G-responses peak at higher levels of L_A, while B-naming responses are not supplanted by Bk-naming until $L_A/L_C > 2$.

To simplify the chromatic responses, it is convenient to assume that Green (G) and Red (R) are complementary opposites, allowing their color-naming functions to be combined into a single difference function $\mathrm{GR}(\lambda_C,L_A) = \mathrm{G}(\lambda_C,L_A)-\mathrm{R}(\lambda_C,L_A)$. Similarly, the Blue–Yellow difference function is $\mathrm{BY}(\lambda_C,L_A)=\mathrm{B}(\lambda_C,L_A)-\mathrm{Y}(\lambda_C,L_A)$.

Further, by assuming that these difference functions are orthogonal, they can be reduced to a single angular hue coordinate: $\mathrm{H}(\lambda_C,L_A)=\arctan(\mathrm{GR}/\mathrm{BY})$. The premise here is that GR and BY are sine and cosine functions, respectively, of the Hue angle (H) [10]. H ranges from 0° for "unique blue" to around 270° for "unique red," while the quadrant 270° to 360° contains short-wavelength violet (and also nonspectral purples). We will return to this function shortly.

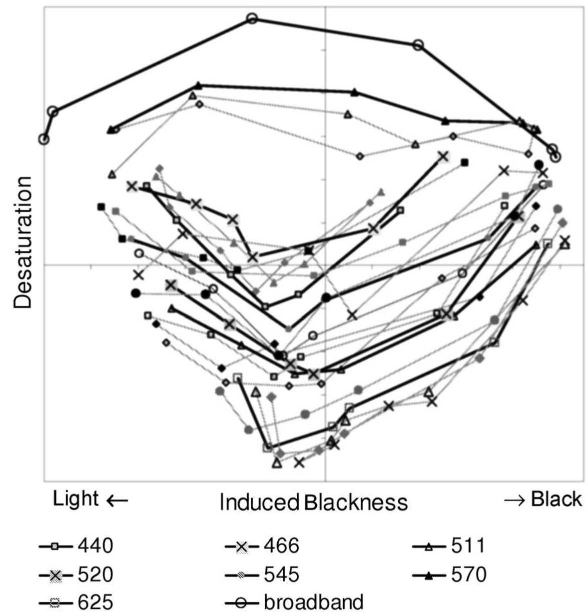

Fig. 2. $D3/D4$ projection of the MDS solution (achromatic plane). Horizontal axis $D3$ = Induced Blackness; vertical axis $D4$ = Desaturation. Units along both axes are arbitrary. For each λ_C, a line connects the six points—all marked with the same (arbitrary) symbol—representing the six stimuli with the same λ_C but different annular intensities. Eight lines are identified as examples.

B. Color space representations

MDS solutions with dimensionality ranging from 2 to 5 were fitted to the 156-by-156 covariance matrix. The respective values of $Stress_1$ were 19.2%, 8.8%, 6.0%, and 4.8%. We opted for the four-dimensional (4D) solution since the fourth dimension was the last to provide a substantial improvement in fit (see [24]). This solution consists of 156 points in 4D space, each located by coordinates $\{x_{i1},x_{i2},x_{i3},x_{i4}\}$. Plausible interpretations could be found for its axes (labeled $D1,D2,D3,D4$) but not for the additional axis of a five-dimensional solution. The coordinates of color points in this 4D color space are shown elsewhere, plotted against wavelength ([25], Fig. 1).

$D1$ and $D2$ of this 4D color space reflect the two perceptual chromatic systems: x_{i1} ("green/red") and x_{i2} ("blue/yellow") are very similar to the difference functions GR and BY, derived directly from the color-naming data in Fig. 1.

Conversely, all the achromatic content of the color-naming descriptions is channeled into $D3$ and $D4$, which are plotted in Fig. 2. The six stimuli with a given λ_C are marked with the same (arbitrary) symbol and connected by a line. In each case, the line follows a gradient from the dimmest annulus (at the left) to most intense annulus (at the right). Note, in particular, that the six broadband-center stimuli (uppermost line in Fig. 2) are dispersed along $D3$ and are all at the positive extreme of $D4$.

We interpret $D3$ as "strength of contrast-induced blackness." Equivalently, by reversing its polarity and taking Light and Black as opposites, it could be interpreted as Lightness, loosely comparable to Luminance (cf. Heggelund's "Luminous / Black" variable, [15]). Bimler *et al.* [25] examined some of the properties of this variable.

Figure 3 shows how this "Induced Blackness" quality x_{i3} interacts with Hue angle for the 150 combinations of wavelength and luminance contrast. Again, lines link the stimuli with the same λ_C but different annular luminance, and clearly the lines are not vertical. That is, spatial contrast not only determines the location of the chromatic center along the Blackness / Lightness continuum, it also affects its *hue*. For instance, as annulus intensity increases, a 560 nm center shifts from containing green and yellow in equal parts to appearing much more green than yellow (Fig. 2). For comparison, Fig. 3(b) demonstrates the BB shift by plotting Hue angle and central luminance L_C from an earlier study where stimulus luminance *objectively* varied and no contrast was present [7]. The effects of decreasing L_C (vertical axis) on the combination of color terms used to describe some wavelengths are qualitatively similar to those of induced blackness.

As noted, the highest values of x_{i4} are for broadband-center stimuli. This prompts an interpretation of $D4$ as "Desaturation," with the most saturated centers at its negative extreme. At the lowest L_A levels, plotting x_{i4} against λ_C produces a curve (not shown here) that replicates the direct ratings of desaturation obtained from a hue-scaling study of aperture-mode stimuli [8]. The x_{i4} values also coincide with the Desaturation axis found in a MDS analysis of similar data in which Black was not among the response options [7].

Holding λ_C constant and starting at the lowest level of L_A, the values of x_{i4} decrease with increasing L_A (as White-responses dwindle) and then increase again as Black-naming comes to dominate the responses, producing V profiles in Fig. 2. These λ_C curves are displaced vertically by a wavelength-dependent quality of "innate saturation." Figure 4(a) plots x_{i4} against L_A:L_C and λ_C, for another view of these V profiles and their varying vertical

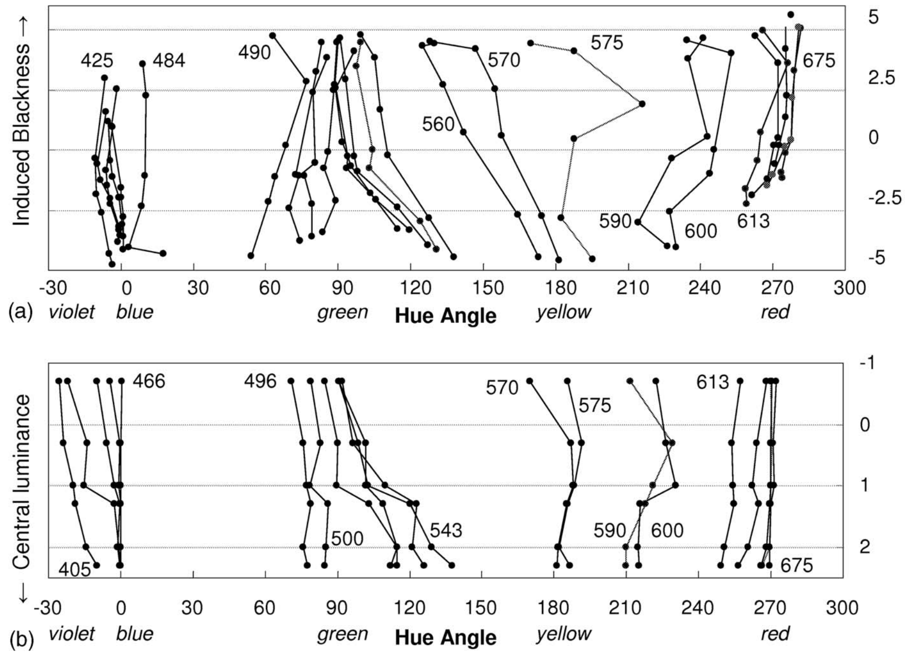

Fig. 3. Hue angle (in degrees; horizontal axis) for each λ_C, showing the effects of (a) Induced Blackness x_{i3} (vertical axis) and (b) luminance of the chromatic center, L_C ($\log \mathrm{cd/m^2}$). Vertical-axis scale in (b) is reversed for parity with (a).

displacements. At the highest L_A, some of the decline in chromatic quality can be ascribed to entropic scattering, in which light from the annulus is scattered within the eye and obscures the relatively dim light from the center ([4], Table 1). Note that the variation of x_{i4} is smallest for yellow lights ($\lambda_C \sim 570-575$ nm). The proportion of

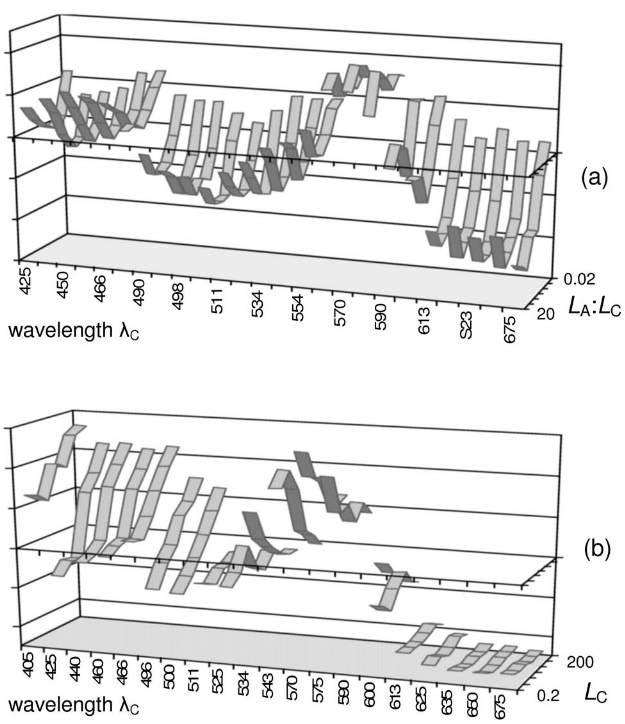

Fig. 4. Desaturation (vertical axis) as a function of λ_C (horizontal axis) and a second variable (third axis, out of the plane of the page). Second variable is (a) spatial contrast and (b) central luminance L_C. The list of wavelengths used to provide (b) does not overlap completely the wavelengths in the present research.

Yellow-responses does decline with increasing L_A; however, according to the MDS outcome, this indicates contrast-induced blackness rather than a loss of saturation *per se*.

It is worth emphasizing that the changes in saturation produced by *objectively* varying a light's intensity are quite different (Fig. 4(b); see also [7], Fig. 4(b)). Specifically, as luminance L_C decreases, short-wavelength blue lights become more saturated, more distinct from White, while mid-wavelength yellow lights become "washed out" [7].

It might seem that the hue shift shown in Fig. 3(a) is an artifact of this saturation shift and is explicable purely by the decline in Yellow-responses at higher L_A. However, this is not so, since a hue shift is evident even when L_A is small. Note also that the chromatic axes $D1$ and $D2$ are in theory corrected for the saturation effect, but a hue shift is still apparent when we plot Induced Blackness against an alternative hue angle $\Theta(\lambda_C, L_A)$, based on x_{i1} and x_{i2} rather than on the difference functions GR and BY.

Figure 2 shows that the lines plotting the $D3/D4$ combinations for the different λ_C all reach their minima of $D4$ (vertical axis) at about the same $D3$ value (horizontal axis). In other words, when spatial luminance contrast is adjusted to maximize the central saturation, it also induces about the same extent of blackness, independent of wavelength. These two qualities are linked. However, the luminance ratio (spatial contrast) required to reach this maximum-saturation (MaxS) criterion is *not* constant.

For a given λ_C, the MDS solution contains six points, one for each L_A. Plotting those six values of x_{i4} against $\log(L_A/L_C)$ forms the appropriate line in Fig. 4(a); this is fitted by a quadratic curve (using least-squares regression). The MaxS ratio for the wavelength is given by the minimum of this curve. We label this ratio MaxS(λ_C), because it is a function of λ_C, plotted in Fig. 5. This ap-

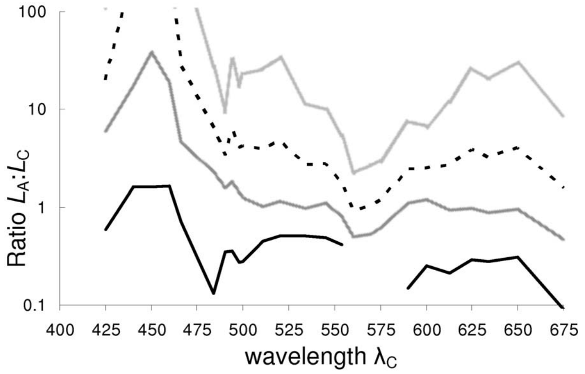

Fig. 5. Luminance ratio L_A:L_C predicted to reach maximum-saturation function MaxS(λ_C), plotted as black curve. Dark gray, dashed, and light gray curves indicate the ratio predicted to produce $x_{i3}=0,2,4$ (i.e., to induce three specific levels of blackness induction), as a function of λ_C. Abscissa shows wavelength λ_C of the chromatic central field.

proach is easier than finding MaxS(λ_C) by interpolation from the raw data. The MaxS criterion is not the same as finding the L_A/L_C ratio that *balances* the W- and Bk-naming responses for a given λ_C (i.e., equal to "W-Bk responsivity" [26]).

Returning now to the third axis, a similar approach allows us to interpolate among the six x_{i3} values produced by various levels of contrast for a given λ_C. Generally these were a good approximation to a sigmoid function: $x_{i3} \approx \tanh(a+b\log(L_A/L_C))$. For each λ_C we determined a and b by regression. Choosing three values of x_{i3} and solving for L_A/L_C resulted in the other three curves shown in Fig. 5. Each curve shows the contrast required to induce a desired degree of blackness into the center (for instance, to reach the point of total blackness where no color remains). All these curves show certain key features: a peak at each end of the spectrum and a secondary peak at around 525 nm, separating two troughs at about 480 and 550 nm.

4. DISCUSSION

In the language of color description, "red" and "green" form the polar extremes of one dimension of color experience; they are not used together to describe the same hue. In the same way, "blue" and "yellow" constitute the poles of a second chromatic dimension. Hering [27] yoked "white" and "black" as a third pair of polar opposites, but their behavior differs in certain ways from the previous pairs. First, black and white can coexist [17,28], so that a given shade of gray might be described as containing black and white in equal amounts. Second, "blackness" is not observed in isolation and cannot be examined in the simplified situation of aperture mode (total absence of visual stimulation produces the experience of *eigengrau*). Blackness exists only as part of an environment, and must be induced by contrast with a lighter color elsewhere in the visual field (spatial contrast) or immediately preceding the test stimulus (temporal contrast [29]). Shades of gray and brown are not part of the gamut of aperture-mode color either, since they contain an element of black [30,31] and are observed only in the company of a lighter stimulation to provide context. Volbrecht and Kliegl [32] reviewed the phenomenological debates and the empirical literature around blackness perception.

Moreover, Evans and Swenholt observed that "the continuum of color perceptions of a color stimulus seen against a variety of backgrounds is four dimensional"—not three-dimensional, as one would expect if Black and White were the mutually incompatible poles of a single dimension ([33], p. 628). Evans and Swenholt argued that in the presence of spatial contrast, the saturation and "gray content" (the opposite of the color "fluorence") of a central stimulus can be manipulated independently.

Again, Logvinenko and Maloney [12] pointed out that there are two independent variables to be deduced from an achromatic object when it appears against a background: the absolute illuminance and the object's relative reflectance. These authors elicited judgments of similarity among stimuli of varying luminance and spatial contrast. MDS analysis of these judgments showed that achromatic stimuli occupy a two-dimensional gamut (see also [16,17]).

In the present study it was convenient to map the achromatic plane in terms of a bipolar axis of Induced Blackness, and a second axis of Desaturation (similar to [16]). Note, however, that other pairs of achromatic axes are possible [13,14]. For instance, one could rotate the achromatic plane through 45° to new axes: a unipolar Lightness axis and a second, orthogonal, unipolar axis of Darkness (diagonal axes in Fig. 6). This would have no effect on how to interpret the chromatic aspects of the stimuli. Izmailov and Sokolov [16] and Izmailov *et al.* [24] described a hyperspherical model, with Black and White as separate achromatic axes, to account for color discrimination.

It would be of interest to extend the present methodology by varying the chromatic purity and luminance L_C of

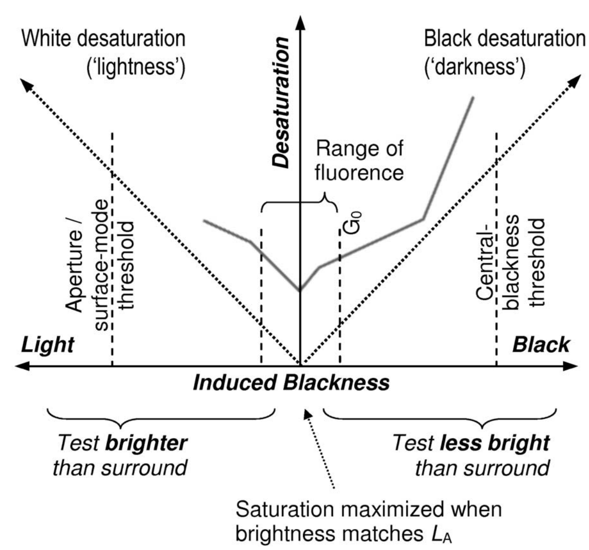

Fig. 6. Schematic diagram of achromatic plane. Example of empirical V-profile shows locations of 494 nm stimuli. Diagonal lines indicate unipolar axes of Darkness and Lightness (more specifically, Black Desaturation and White Desaturation). These arise from two achromatic qualities created by spatial contrast: Induced Blackness (or with polarity reversed, Lightness) and Desaturation. Dashed vertical lines indicate some of the thresholds used to measure induced blackness (see text for further details).

the monochromatic test field. In the present research, though, only two stimulus parameters were varied: the test-field wavelength and degree of contrast. Under these conditions, the stimuli can be regarded as points on a locally two-dimensional surface embedded within the 4D continuum of color perception. The color points are confined to the surface of the 4D MDS solution: they do not sample its interior.

With monochromatic stimuli, the desaturation produced by contrast is superimposed on variations in the "innate saturation" of the chromatic test fields [Fig. 4(a)]; when plotted in a color space (e.g., CIELAB), prismatic lights do *not* form a circular spectrum around *W* at the center. The mechanics of color processing produce a locus that is more of a distorted triangle, with corners in the Blue, Green, and Red regions of the spectrum, farthest from *W*. Conversely, at the middle of one triangle side linking Green to Red, monochromatic yellow light at ~570 nm is relatively close to the center, indicating it to be lower in saturation and brightness. Near the middle of another side linking Blue to Green, blue-green light at ~480 nm is also relatively desaturated.

As a corollary of their greater saturation, some wavelengths have a higher hue-purity threshold: they can be diluted with a larger ratio of white light before they lose all visible hue (otherwise termed "chrominance" or "coloring power," [23], p. 342). A larger amount of induced blackness is also required to completely extinguish their hue. This might seem to blunt the argument that blackness induction *per se* depends on test-field brightness: Could it be that blackness induction is the same for all λ_C, with some wavelengths requiring a higher ratio L_A/L_C to reach a given criterion of blackness (see Fig. 5) simply because of a higher "resistance to dilution"? However, this alternative explanation does not account for the variation across wavelengths of the maximum-saturation ratio $\mathrm{MaxS}(\lambda_C)$. The similarity between $\mathrm{MaxS}(\lambda_C)$ and brightness function B_λ affirms that brightness of the central light is a crucial parameter in the induction of blackness by spatial contrast: a fixed level of luminance contrast induces more blackness into less-bright wavelengths (e.g., 570 nm).

For a given λ_C, the stimuli produced by varying the single parameter L_A are sampled from a one-dimensional locus within the achromatic plane, so for the present stimuli, Desaturation and Induced Blackness are interdependent. More specifically, the lines linking stimuli for each λ_C in Fig. 2 show a V-shaped relationship between Desaturation and Induced Blackness. The chromatic test field is most saturated when its brightness is balanced by the luminance of the surround, inducing neither blackness nor whiteness. The variations of innate saturation along the spectrum displace these V curves vertically along the Desaturation axis.

We are not aware of any *direct* measurements (ratings) of central saturation across the range of spatial contrast. Instead, numerous studies have examined the spatial contrast required to reach particular thresholds, as a function of λ_C. Evans and Swenholt ([34], Fig. 3) plotted the luminance ratio where the last element of grayness vanished from the stimulus appearance and "fluorence" began. They coined the name "fluorence" for a phenomenal property of surface-mode color: the impression of a fluorescent surface created when a colored stimulus is seen against a white surround of similar luminance. This "perceptible grayness," or G_0 criterion, is similar in concept to the function $\mathrm{MaxS}(\lambda_C)$ (Fig. 5) but is measured in an entirely different procedure. Reassuringly, it displays the same features: troughs at 480 and 570 nm, peaks toward each end of the spectrum, and a secondary peak at 510 nm.

A different criterion is the ratio required to induce complete blackness and remove the last trace of hue from the center. This ratio, as Evans and Swenholt [34] reported, formed a curve in parallel with G_0 that, however, was displaced vertically along the ratio axis by a log step. Shinomori *et al.* ([18], Fig. 3) considered this same total-blackness aspect of spatial contrast. They found that when the central light was a mixture of two wavelengths, the luminance ratio required to meet the criterion was not what one would predict by simple interpolation from the ratio for each wavelength separately. That is, blackness induction is nonadditive—which distinguishes it from the luminance function V_λ, which *is* additive. Shinomori *et al.* translated their blackness-induction function from relative to absolute terms—the photon flux in the annulus required to induce the complete-blackness criterion—and concluded that this "spectral efficiency of blackness function" was similar to the brightness function B_λ, if not identical. Like B_λ, blackness induction showed diagnostic "notches" at 480 and 570 nm.

The other extreme of spatial contrast is where the surround is not lit at all, so that the visual field is dark except for a small uniform colored center. This is the limiting case of aperture mode. Aperture mode is often regarded as a particularly simple form of color perception. But although the surround is black, it still exists, and the present data show that a sufficiently dark surround or background desaturates the center by inducing whiteness into it (in line with Boynton's comment about the low saturation of aperture-mode light [23]). In Heggelund's bidimensional model a transition between aperture and surface-mode color occurs when increasing spatial induction changes the sign of the "Luminous/Black" variable [15]. Uchikawa *et al.* [35] examined the level of surround luminance associated with this transition as a function of test-field spectral composition. The threshold was much lower than "perceptible grayness" but followed a similar spectrum, determined by the brightness of the test field.

Thus the *brightness* of a central stimulus, rather than its luminance, determines the degree of blackness induced into it. In contrast, there is a broad experimental consensus that the spectral composition and brightness of the *inducing annulus* is irrelevant [36–38], leaving its luminance as the crucial parameter. In the present data, this asymmetry is most evident in the observations where the surround has the same luminance as the center, $L_A = L_C$. The yellow stimuli, which are only marginally brighter than the surround (due to their low chrominance), contain a component of Black (Fig. 1). In contrast, the blue stimuli are significantly brighter and attract a significant number of White-responses.

We note in passing that the color temperature of the broadband annulus was lower than ideal (2850 K), with a slight yellow tinge. However, the lesson from the previous paragraph is that this slight yellowness was not crucial to blackness induction. The surround hue does influence *chromatic* induction, but even here, Evans and Swenholt [33] found only minimal differences in the effects of spatial contrast when they switched the color temperature of the broadband surround from 7000 K to 3000 K.

Gordon and Shapley [39] used the opposite geometry (an achromatic center and a chromatic surround) and a different paradigm (induction of the complementary hue into the center). Once again, spatial induction was mediated by brightness—in their paradigm, that of the surround. Any brightness-defined boundary appeared to inhibit chromatic induction, which was strongest when center and surround were equally bright. This is consistent with Heggelund's prediction ([15], Fig. 12) that colors will be less affected by the mechanisms of color constancy when in aperture mode, appearing to be self-luminous and dissociated from the visual environment.

5. CONCLUSIONS

Evidence has already been presented that spatial contrast involves an interaction between *brightness* in a given chromatic region of the visual field, and *luminance* in an adjacent inducing region. Any complete model of color processing must incorporate both of these parameters. It is possible that this asymmetric interaction is a feature of the specific retinal geometry probed in the current study: a foveal chromatic test field and a parafoveal inducing region (an annulus with 2° inner and 6° outer diameters).

Figure 7 represents an attempt to incorporate Brightness within the stream of color processing and to indicate its relationships to other qualities, including its role in spatial contrast. The model begins at the left, indicating retinal/early cortical processing that encodes the color signal in terms of the (L−M) and S_0=S−(L+M) chromatic mechanisms, or channels. The initial inputs to these channels and to the Luminance signal L are linear combinations of cone outputs. These cone-opponent channels should not be conflated with the classical opponent pairs of the Hering [27] perceptual model (see also Hurvich and Jameson [40]) defined from the sensations of unique Red and Green, Blue and Yellow. These arise at later, relatively uncharted stages of cortical processing [41]. The opponent-color terms are used to collect data, but this does not signify that they need to dominate the data interpretation.

The diagram also includes channels for the achromatic axes $D3$ and $D4$ of the MDS solution obtained in this study. Here we are interpreting the solution literally while assuming that each axis corresponds to some objective phenomenon (i.e., a quality represented at the neural level). For comparison, Shinomori *et al.* ([18], Fig. 11) presented a similar model, corresponding to Boxes 1–5 of our Fig. 7, since it was not intended to encompass saturation effects. That model also excluded Brightness, which the authors concluded to differ from the "spectral efficiency of blackness function." Unlike Shinomori *et al.*, we are not yet in a position to quantify parameters or test predictions, so the present diagram is tentative and speculative. It is presented mainly to provide a visual explanation and a framework for our conclusions rather than as a definitive circuit diagram for the architecture of cortical anatomy. It seems premature to associate the hypothetical channels with the physiologically distinct magno-, parvo-, or koniocellular systems, or to locate the processing boxes in particular layers of striate cortex [42].

We note in passing that Valberg and Seim [43] explain the nonlinear features of color vision, brightness, and blackness induction in terms of the intrinsic nonlinearity

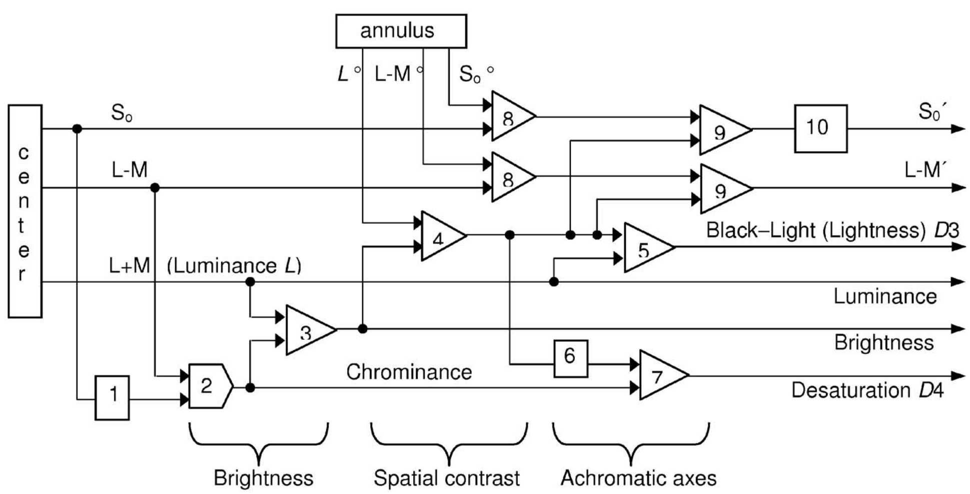

Fig. 7. Model of multistage processing of chromatic information. Boxes indicate loci and operations contributing to the influence of spatial luminance contrast and responsible for color appearance effects. See text for details. 1. Compressive, *asymmetric* nonlinearity on S_0 channel (produces Luminance / Saturation effect). 2. Calculation of chrominance: $X=|S_0|+|L-M|$ (produces failure of additivity). 3. Brightness B=Luminance+βX for some parameter β. 4. Achromatic contrast (AC) between central Brightness and surround Luminance: AC=$B-L°$. 5. Lightness: $D3$=Luminance+γ AC. Induced Blackness=same axis with reverse polarity. 6. Desaturating signal=$|B-L°|$ =absolute value of AC. 7. Saturation: $D4=X-|AC|$ (i.e. chrominance, reduced by Desaturating signal). Desaturation is same axis with reverse polarity. 8. Chromatic contrast: $S_0°$ and (L−M)° signals from surround induce complementary hue into center. 9. Achromatic contrast signal inhibits or promotes the chromatic signals S_0 and (L−M) (necessary for induced blackness to affect hue). 10. Expansive, *symmetric* nonlinearity on the S_0 channel (produces Luminance/Hue effect, or BB hue shift).

of opponent cells within the parvo pathway. In their approach, qualities such as brightness emerge as epiphenomena, and there is no need to postulate dedicated neural pathways or mechanisms.

Our model postulates a "chrominance," or "innate saturation," signal (*X*), generated through a nonlinear combination of the S_0 and (L−M) channels (Box 2). It can be regarded as a first approximation as the distance in color space between the hue in question and White. Chrominance in turn combines additively with Luminance L_C (Box 3) to produce the Brightness signal B. B is conceptually linked to saturation: in the Helmholtz—Kohlrausch effect (e.g. [44]), a saturated hue is seen as brighter than some equally luminant but less saturated hue. Thus W is the limiting case of zero chroma, while monochromatic lights are at the other extreme, with maximal chroma and Brightness.

In order for the brightness of the test field to mediate spatial contrast, the B signal must appear prior to lateral interactions and the computations of contrast. Box 4 shows a subtractive interaction between B and the L_A signal from adjacent regions of the visual field, yielding a bipolar achromatic contrast signal AC. AC in turn modulates the test field L_C at Box 5, increasing or reducing it according to the sign and extent of spatial contrast, resulting in the perceived lightness (or blackness) of the center (Induced Blackness axis $D3$ in Figs. 2 and 6).

However, although L_C and the degree of contrast both contribute to the perceived lightness of a chromatic test field, their effects must diverge in some way. If the parameters were interchangeable, so that it was always possible to shift central luminance by some ΔL_C while adjusting the spatial contrast so as to cancel out the effect of ΔL_C on the achromatic content of the test field, then that achromatic content would be (locally) one dimensional. This is contrary to the evidence that achromatic quality is two dimensional under conditions of contrast [12,17,33].

The model incorporates this by rectifying the AC signal (Box 6) and subtracting its absolute value from the chrominance X (Box 7). The output of Box 7 is *observed* saturation, a sign-reversed version of the Desaturation axis $D4$ of Fig. 2. Thus we see a V-shaped relationship between surround luminance and desaturation [Fig. 4(a)]. Some intermediate level of induced blackness x_{i3} minimizes the desaturation of the test field (Fig. 2). This optimal level of x_{i3} is constant across λ_C, although the surround luminance required to induce it is the wavelength-dependent function $\mathrm{MaxS}(\lambda_C)$. At this criterion, the observed saturation is the chrominance without attenuation by positive or negative spatial contrast.

Objective variations in L_C affect saturation differently. Figure 4(b) shows a monotonic shift, with its direction depending on the S_0 signal produced by the test field: saturation increases with L_C for short wavelengths (positive S_0) and decreases for longer wavelengths (negative S_0). This "Purdy saturation shift" implies an asymmetric nonlinearity within the S_0 opponent channel [9] (Box 1), before the locus of spatial contrast. This still leaves the locus of nonlinearity undefined; it could occur at a number of places along the opponent channel, from its origin in short-wavelength cone responses up to its contribution to the Saturation signal.

Consider now the familiar Bezold–Brücke hue shift associated with L_C. This can be explained if the S_0 channel undergoes an expansive nonlinearity relative to the (L−M) channel, so that increasing the intensity of a hue changes its chromatic description by increasing the relative proportion of the S_0 signal [7]. This second nonlinearity is symmetric: the magnitudes of a negative and a positive S_0 signal both increase with luminance, so that where S_0 is positive, blue-greens and purples become bluer, while where S_0 is negative, yellow-greens and oranges become yellower [Fig. 3(b)]. Exceptions are the invariant hues, which retain a constant appearance across a range of luminance levels. These lie on one or other cardinal axes—they are characterized by a null signal on one of the chromatic channel, which remains null after any nonlinearity.

Figure 3(a) shows that a very similar hue shift results from varying the blackness induced by spatial contrast. This implies a third role for the brightness-mediated spatial-contrast signal AC: at some stage of processing, it must reach the (L−M) and S_0 channels and amplify or attenuate their signals (Box 9 in Fig. 7). A second implication for the architecture of visual processing is this must occur *before* the locus of the S_0 nonlinearity at Box 10.

Why the brightness of a chromatic test field should determine spatial contrast (interacting with the luminance of the surround) is secondary to the question of why we have a percept of "brightness" at all. It is not immediately obvious how "brightness" assists our responses to color, in addition to the information already contained in the percept of luminance. Uchikawa *et al.* [35] suggest that the right context for understanding these issues is the ecological value of being able to distinguish self-luminous stimuli from stimuli that are reflective surfaces. The distinction depends on how much light a surface might plausibly reflect: if the light flux from some region of the visual field exceeds this limit, then the region is self-luminous and should stand out subjectively from the background (according to Heggelund [15], it will be decoupled from color-constancy interactions). Calculating the limit accurately is complex: it depends on the chroma and hue of the region in question, on the inferred ambient illumination, and on constraints of physics. Uchikawa *et al.* argue that stimulus Brightness is not perfect, but it allows a good approximation to calculating the limit. Essentially Brightness allows the visual system to segregate self-luminous stimuli from their visual backgrounds—and in passing, to generate the percepts of "aperture-mode" and "surface-mode" color.

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