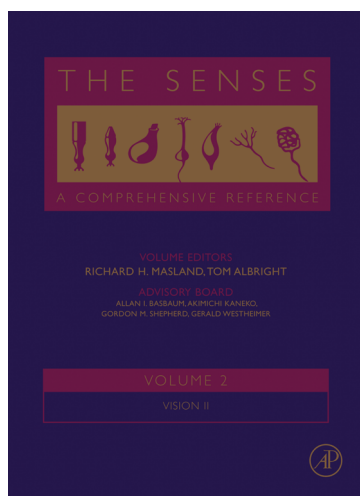


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2.08 Color Appearance

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2.08.1 Specifying and Describing Color

Because of the importance of color measurement in the materials, printing, electronic imaging, and lighting industries, a large technical vocabulary has evolved based on international agreement. Recommendations of the Commission Internationale de l'Eclairage (CIE) concerning colorimetry and a color-appearance model are available in two technical reports (CIE, 2004a; 2004b). Colorimetric terms and formulas are introduced here only as they are needed, and the specification of color appearance with reference to

proprietary color-order systems is not discussed (e.g., see Wyszecki, G. and Stiles, W. S., 1982; Hunt, R. W. G., 1998; Fairchild, M. D., 2005).

2.08.1.1 The Color Signal and Spectral Sampling

The light reflected from an illuminated scene or emitted by an electronic display system produces a stimulus to the human eye consisting of a distribution of spectral radiance $c(\lambda)$ over wavelength λ at each point in the field of view. For reflected light, this color signal $c(\lambda)$ (Buchsbaum, G. and Gottschalk, A., 1983) is

the wavelength-by-wavelength product of an illuminant spectrum $E(\lambda)$ and the spectral reflectance $R(\lambda)$ at each point in the scene; that is, $c(\lambda) = E(\lambda)R(\lambda)$, in suitable radiometric units. Figure 1, first column, shows the normalized spectrum $E_1(\lambda)$ of light from the sun (second row) illuminating a flower stamen with spectral reflectance $R_1(\lambda)$ (third row), giving the color signal $c_1(\lambda) = E_1(\lambda)R_1(\lambda)$ (fourth row).

The color signal, imaged onto the retina, is normally sampled by the long-, medium-, and short-wavelength-sensitive cone photoreceptors with spectral sensitivities $L(\lambda)$, $M(\lambda)$, and $S(\lambda)$, respectively (Figure 1, fifth row). The corresponding cone excitations l_1 , m_1 , and s_1 , are obtained by integrating the product of $c_1(\lambda)$ with, in turn, $L(\lambda)$, $M(\lambda)$, and $S(\lambda)$ over wavelength λ .

If any two spectra, for example $c_2(\lambda)$ and $c_3(\lambda)$ in Figure 1 (second and third columns, fourth row), produce triplets (l_2, m_2, s_2) and (l_3, m_3, s_3) of excitations at a point that are the same, then they are visually indistinguishable, for after absorption all information about their spectral origins is lost (Naka, K. I. and Rushton, W. A. H., 1966). But as is evident here, identical triplets do not imply identical color signals: $c_2(\lambda)$ and $c_3(\lambda)$ are different functions of λ . In general, color signals need more than three numbers to specify them, experimentally about eight with natural scenes (Nascimento, S. M. C. *et al.*, 2005b). This ambiguity – of different spectra producing the same cone excitations, and therefore the same color information – is known as metamerism (Wyszecki, G. and Stiles, W. S., 1982; Hunt, R. W. G., 1998). Metamerism can arise from differences in illuminant spectra or reflectance spectra or other viewing factors, and it sets a limit, even under constant viewing conditions, on how well color can be used to represent the spectral properties of surfaces.

2.08.1.2 Tristimulus Values

With just three classes of cones in the normal eye, the colors of stimuli could be specified by triplets of cone excitations, as in Figure 1, but for historical reasons, the established system of colorimetry is instead based on color-matching functions $\bar{r}(\lambda)$, $\bar{g}(\lambda)$, and $\bar{b}(\lambda)$, which represent the amounts, sometimes negative, of three monochromatic, primary lights needed to match a monochromatic light of constant radiant power at each wavelength λ (Wright, W. D., 1928–1929; Guild, J., 1931). For computational convenience, these color-matching functions – standardized internationally in 1931 by the CIE – were transformed to a new set of

functions $\bar{x}(\lambda)$, $\bar{y}(\lambda)$, and $\bar{z}(\lambda)$ with non-negative values and with $\bar{y}(\lambda)$ equated to $V(\lambda)$, the daylight luminance sensitivity of the eye. An arbitrary color signal $c(\lambda)$ in this system is specified by a triplet of tristimulus values X , Y , and Z , obtained by integrating the product of $c(\lambda)$ with, in turn, $\bar{x}(\lambda)$, $\bar{y}(\lambda)$, and $\bar{z}(\lambda)$ over wavelength λ (for details, e.g., see Wyszecki, G. and Stiles, W. S., 1982; Fairchild, M. D., 2005).

The parallel between the calculation of tristimulus values X , Y , Z and of cone excitations l , m , s is not accidental: the functions $\bar{x}(\lambda)$, $\bar{y}(\lambda)$, $\bar{z}(\lambda)$ are a linear transformation of the cone spectral sensitivities $L(\lambda)$, $M(\lambda)$, $S(\lambda)$, and the tristimulus values X , Y , Z are the same linear transformation of the cone excitations l , m , s .

A two-dimensional chromaticity space with coordinates (x, y) can be derived from tristimulus values X , Y , Z by normalizing; that is, $x = X/(X + Y + Z)$ and $y = Y/(X + Y + Z)$. In this space, the spectral colors form a horseshoe-shaped arc around the point $(1/3, 1/3)$ representing a white with constant radiant power across the spectrum. But the distance between a pair of points, 1 and 2 say, defined by the Euclidean formula $[(x_1 - x_2)^2 + (y_1 - y_2)^2]^{1/2}$ gives a poor guide to the perceived color difference between the corresponding stimuli, which varies according to where the pair of points lies in the space and the orientation of the line joining them. This chromaticity space is perceptually nonuniform; so also is the space of tristimulus values X , Y , Z (Wyszecki, G. and Stiles, W. S., 1982).

2.08.1.3 Related Colors

Although the tristimulus values X , Y , Z of a light (or cone excitations l , m , s) are sufficient to specify the color of a light, and the coordinates (x, y) its chromaticity, they do not describe its appearance: its hue, saturation, lightness, and so on. For example, a monochromatic light of 590 nm, which has chromaticity coordinates $x = 0.575$, $y = 0.424$, appears orange when viewed in isolation in a dark field but brown if surrounded by a brighter, white light.

In natural viewing, colors are normally perceived in relation to each other, as part of a larger scene, and are technically termed related colors (Fairchild, M. D., 2005). Canonical examples of related colors include, in addition to brown, the colors olive green, khaki, and navy blue. Any system for representing color appearance must therefore include some information about the context of the color.

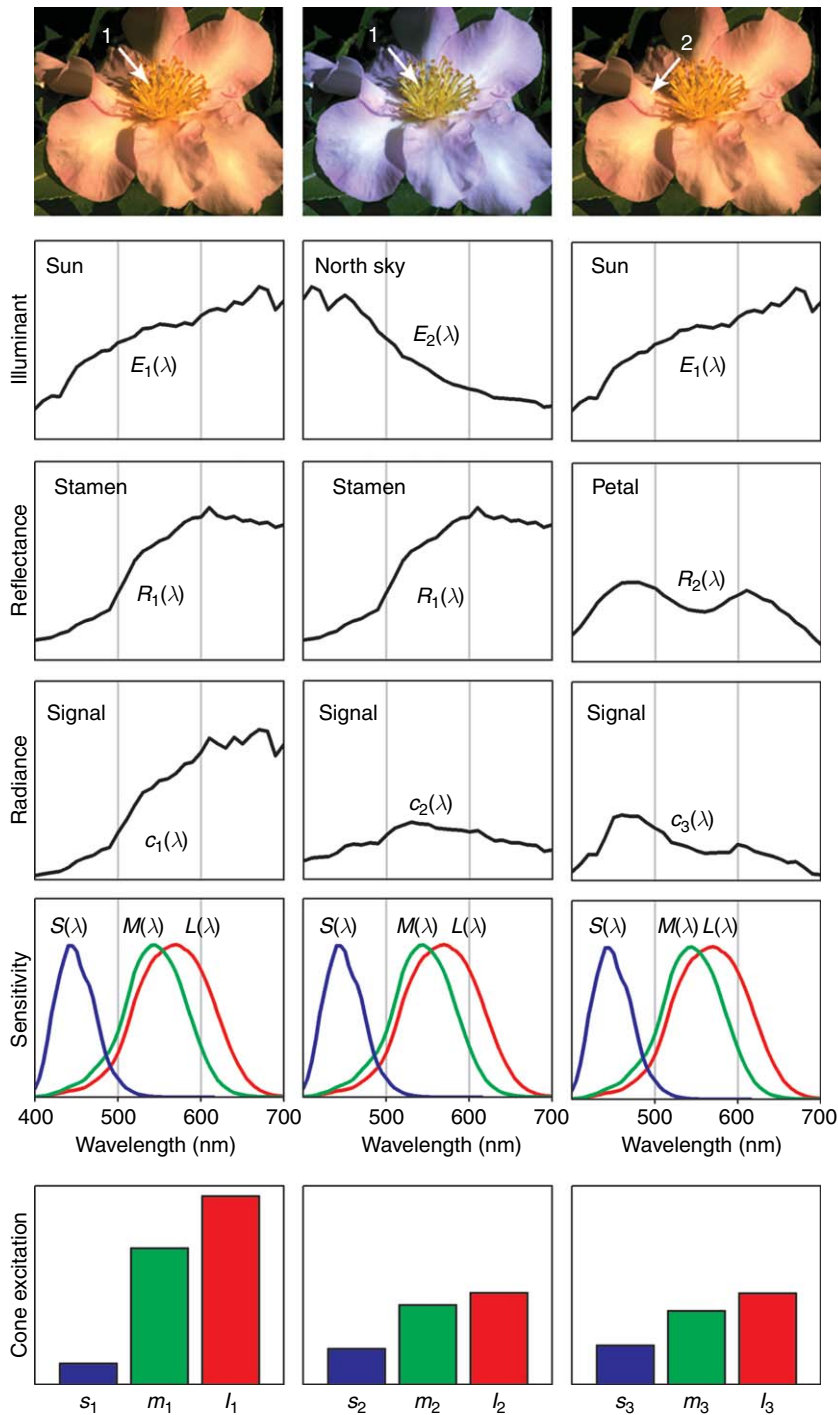


Figure 1 Two areas of a flower under different colored illuminations and the resulting pattern of cone excitations. The spectral reflectance $R_1(\lambda)$ of the stamen (1) under light with spectrum $E_1(\lambda)$ from the sun (correlated color temperature 4000 K) gives a color signal $c_1(\lambda)$ with greatest power at long wavelengths (first column) but a much more even distribution $c_2(\lambda)$ (second column) under a light with spectrum $E_2(\lambda)$ from the north sky (correlated color temperature 25 000 K). As a result, there are marked differences in the triplet of cone excitations (l_1, m_1, s_1) and (l_2, m_2, s_2) (bottom row). By contrast, the spectral reflectance $R_2(\lambda)$ of the petal (2) under sunlight (column 3) gives a different color signal $c_3(\lambda)$ but an almost identical pattern of cone excitations (l_3, m_3, s_3), showing how the effects of illuminant and reflectance spectra may be indistinguishable at a point.

2.08.1.4 CIELAB Color Space

An effect of context is abstracted in CIELAB color space with the specification of a reference white (Wyszecki, G. and Stiles, W. S., 1982; Fairchild, M. D., 2005). This space, defined by the CIE in 1976, has coordinates (L^*, a^*, b^*) , which, for a given color, are calculated as follows. First, the tristimulus values X, Y, Z of the color are normalized against the tristimulus values X_n, Y_n, Z_n of the reference white to give $X/X_n, Y/Y_n, Z/Z_n$. A cube-root transformation is then applied to represent a sensory compression of the response, that is, $(X/X_n)^{1/3}, (Y/Y_n)^{1/3}, (Z/Z_n)^{1/3}$. Finally, a numerical scaling is applied to $(Y/Y_n)^{1/3}$ to give the coordinate L^* and other numerical scalings applied to the differences $(X/X_n)^{1/3} - (Y/Y_n)^{1/3}$ and $(Y/Y_n)^{1/3} - (Z/Z_n)^{1/3}$ to give the coordinates a^* and b^* , respectively. The coordinate L^* defines a lightness axis, a^* a redness–greenness axis, and b^* a yellowness–blueness axis. Values of L^* range from 0 for black to 100 for a perfectly diffusing white (and possibly >100 for specular reflecting surfaces).

Although not intended as a color-appearance system, some color-appearance attributes can be obtained from L^*, a^*, b^* by defining relative colorfulness or chroma C_{ab}^* as $(a^{*2} + b^{*2})^{1/2}$ and hue h_{ab} as an angle $\tan^{-1}(b^*/a^*)$, in degrees, to form a cylindrical coordinate system (Fairchild, M. D., 2005). Saturation is the colorfulness of area judged in proportion to its brightness.

Figure 2 shows some example CIELAB cylindrical coordinates (L^*, C_{ab}^*, h_{ab}) from a natural scene. The hue angles (third coordinate) of the red and

orange petals are 50° and 69° , that is, between the reddish end of the a^* axis and yellowish end of the b^* axis and the hue angle of the purple flower is -57° , that is, between the reddish end of the a^* axis and the bluish end of the b^* axis. The chroma of the points on all three flowers is moderate to high, ranging from 37 to 102, but the chroma of the gray sphere inserted in the scene is low, just 7, although a truly neutral surface would have zero chroma. The flowers and sphere all have similar lightnesses, ranging from 46 to 72.

In CIELAB space, the color difference, denoted by ΔE_{ab}^* between a pair of stimuli, 1 and 2, say, defined by the Euclidean distance formula $[(L_1^* - L_2^*)^2 + (a_1^* - a_2^*)^2 + (b_1^* - b_2^*)^2]^{1/2}$, is perceptually more uniform than the Euclidean distance formula in the untransformed X, Y, Z space, but large nonuniformities remain. CIELAB space is also designed for viewing scenes under a standardized daylight illuminant, and the device of dividing the tristimulus values of a color by the tristimulus values of a reference white is only partly successful in accommodating changes in the illuminant (Terstiege, H., 1972; Fairchild, M. D., 2005).

Since the introduction of CIELAB space, progressively more accurate and comprehensive color-difference formulas and color-appearance models have been developed for colorimetric applications (Hunt, R. W. G., 1998; Fairchild, M. D., 2005). Thus, the non-Euclidean CIE color-difference formula CIEDE2000 (Luo, M. R. *et al.*, 2001) largely corrects the perceptual nonuniformities of the Euclidean formula in CIELAB space. A subsequent color-appearance model CIECAM02 (Li, C. J. and Luo, M. R., 2005) that takes into account simple surround conditions provides formulas for transforming from CIE tristimulus values to correlates of the perceptual attributes of lightness, brightness, chroma, saturation, colorfulness, and hue, and also an approximately Euclidean distance formula for uniform color differences (Luo, M. R. *et al.*, 2006).

2.08.2 Illuminant and Viewing Media

The influence of context on color appearance may be interpreted as a consequence of our visual experience, of seeing colored surfaces surrounded by other colored surfaces in the natural environment (Judd, D. B., 1940). Here the color appearance of an object may serve as a cue to its identity or condition: the greenness of grass, the redness of ripe fruit. But this is

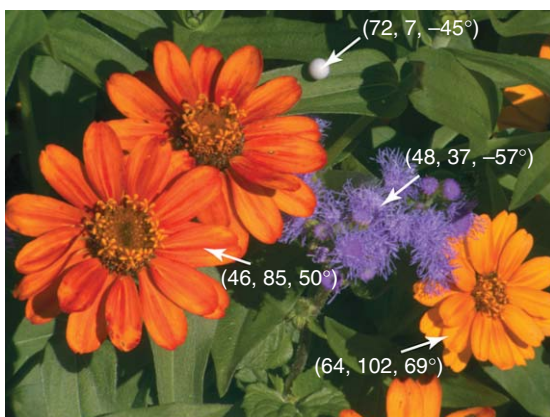


Figure 2 CIELAB cylindrical color coordinates of points in the image of a natural scene under daylight. The lightness, chroma, and hue angle (in degrees) of each point are indicated.

possible only if color appearance correctly represents in some way surface color – the visual correlate of spectral reflectance – within the limits of metamerism (Section 2.08.1.1).

2.08.2.1 Color Constancy

As noted in Section 2.08.1.1, the color signal $c(\lambda)$ reaching the eye is the wavelength-by-wavelength product of the illuminant spectrum $E(\lambda)$ and the spectral reflectance $R(\lambda)$ at each point in the scene. As a representative of surface reflectance, this color signal is confounded with the properties of the illuminant, for example, whether it has more radiant power at long wavelengths (Figure 1, first column, second row) than at short wavelengths (Figure 1, second column, second row), affecting the resulting triplet of cone excitations l, m, s (bottom row).

Yet in everyday experience, the color appearance of surfaces seems fairly stable. As T. Young (1807) pointed out, a sheet of writing paper appears to retain its whiteness whether illuminated by the yellow light of a candle or by the red light of a fire. This stability is summarized in the notion of color constancy: the constant appearance of object or surface color despite changes in the color of the illumination, and, in modern usage, in scene composition and configuration (Maloney, L. T., 1999). Color constancy is a complex phenomenon (Foster, D. H., 2003; Smithson, H. E., 2005), with a long history of analysis, attracting contributions from G. Monge (1789), T. Young (1807), and H. von Helmholtz (1867), and later by Land, E. H. (1959a; 1959b). But it has proved an elusive phenomenon to quantify, for the stability of color appearance seems to vary with the methods used to measure it, as explained later.

2.08.2.2 Separating Illuminant and Reflectance Spectra

How, in principle, can the confounding effect of the spectrum of the illumination on a scene be eliminated from the color signal at the eye? Suppose that the cone excitations l_0, m_0, s_0 corresponding directly to the illuminant $E(\lambda)$ were available, for example, by reflection from a perfectly diffusing white surface somewhere in the scene. Then an approximately unbiased estimate of a surface color might be obtained by normalizing the excitations l, m, s from the light reflected from this surface against l_0, m_0, s_0 , to give $l/l_0, m/m_0, s/s_0$ (cf. Section 2.08.1.4). In this way, if the illuminant contained an excessive radiant

power at long wavelengths, the relatively large value of l would be reduced by the relatively large value of l_0 . These scaled cone excitations would be uniquely linked to surface color within the scene, again within the limits of metamerism (Section 2.08.1.1).

This scaling hypothesis was formulated by J. von Kries (1905) to describe the adaptation of the eye to colored lights, albeit not necessarily globally (Ives, H. E., 1912; Smithson, H. E., 2005). Although better known for its role in modeling color constancy, the hypothesis also provided a powerful experimental technique for estimating the spectral sensitivities of the three cone types from color-matching measurements (Wyszecki, G. and Stiles, W. S., 1982).

Formally, von Kries scaling constitutes a diagonal matrix transformation of cone responses (Terstiege, H., 1972; Worthey, J. A. and Brill, M. H., 1986; Brainard, D. H. and Wandell, B. A., 1992), but in practice the extent of the chromatic adaptation provided by this scaling is restricted. Thus, full perceptual compensation for the illuminant occurs only with unsaturated lights. With saturated lights, perceptual compensation is usually incomplete (Judd, D. B., 1940): the red safelight of the photographic darkroom never appears white (Ives, H. E., 1912).

Despite limited experimental evidence, many models of color constancy, including the multiplication rule used in Land's so-called retinex models (Land, E. H., 1959a; 1959b; 1986), assumed implicitly that the formalism of the scaling hypothesis applies also to lights reflected from surfaces. When tested more directly, it was found that the ratios $l/l_0, m/m_0, s/s_0$ of cone excitations from reflected lights – and not just from those surfaces where one was white – are indeed almost independent of the illuminant (Foster, D. H. and Nascimento, S. M. C., 1994). If cone responses are first transformed so that they are spectrally sharper, for example, by cone-opponent interactions (Foster, D. H. and Snelgar, R. S., 1983; Finlayson, G. D. *et al.*, 1994b), then the independence is even better (Finlayson, G. D. *et al.*, 1994a).

2.08.2.3 Relational Color Constancy

If the eye does not adapt completely to the illumination on part or all of a scene, then color appearance ought to be affected, and, in turn, judgments of surface color. But not all judgments that appear to involve color constancy involve complete chromatic adaptation. For example, in the natural world, surfaces are often seen partly in direct light and partly in shadow, but the shadowed region appears to have the

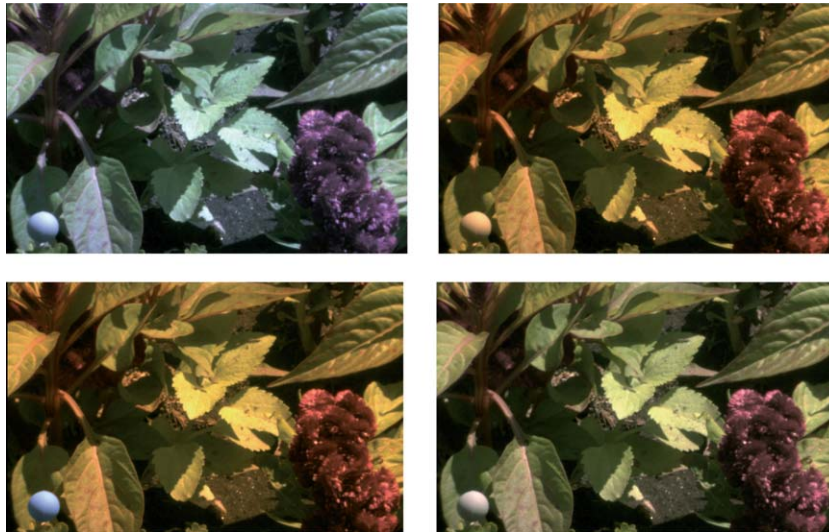


Figure 3 Images of a natural scene containing a test sphere (bottom left in each image) under different illuminations. In the upper left and right images, the illuminant is north sky light (correlated color temperature 25 000 K) and sunlight (4000 K), respectively, and the sphere is covered with gray paint. In the lower left image, the illuminant is sunlight and the sphere is covered with blue-gray paint. In the lower right image, the illuminant is a mixture of sunlight and north sky light (6500 K), and the sphere is covered with gray paint.

same surface color as the unshadowed region, even though it is simultaneously seen to be less bright and generally more blue (Arend, L. E. *et al.*, 1991). This apparently paradoxical separation of percepts was identified by Georg Christoph Lichtenberg in 1793 in a letter to Johann Wolfgang von Goethe thus: “In ordinary life we call white, not what looks white, but what would look white if it was set out in pure sunlight” (Joost, U. *et al.*, 2002, p. 302).

To make effective surface-color judgments in these conditions, an observer could use the perceived color relations between parts of a scene. For example, in Figure 3, in the upper left and upper right images of a scene, the color of the light reflected from the sphere in the bottom left corner is clearly different; nevertheless, it is possible to decide that the sphere has the same surface color by comparing it with, for example, the nearby leaves. By contrast, in the lower left image, although the color of the light reflected from the sphere is the same as in the upper left image, it is possible to decide that the sphere has a different, bluish, surface color, again by comparing it with nearby leaves. In the upper left and upper right images, the perceived relations between the colors are preserved; in the upper left and lower left images, they are not (the lower right image is discussed in Section 2.08.4.4).

Relational color constancy refers to the constancy of perceived color relations under illuminant changes, or other viewing conditions (Foster, D. H. and

Nascimento, S. M. C., 1994), and has an operational interpretation described later (Section 2.08.4.5). It is distinct from the phenomenon of related colors, which requires other colors for their perception.

Notice that the comparisons just described may be made simultaneously with fixed gaze, or sequentially by moving the eye from one image to the other (Cornelissen, F. W. and Brenner, E., 1995), or with fixed gaze and the illumination on the scene changing, or any combination of these. Although some chromatic adaptation does take place with these images, either locally or globally, or both, it is insufficient to eliminate the perceived differences in illumination.

2.08.3 Sensory and Perceptual Cues

If color constancy is achieved partly or wholly by scaling cone responses – or their transforms – to compensate for the color of the illumination on a scene, then information about the illuminant is required. But the illuminant itself may not be visible; for example, the light may come from behind the observer, and there may be no designated perfectly diffusing white surface in the scene from which the corresponding cone excitations l_0 , m_0 , s_0 representing the illuminant can be derived. Other strategies are needed to obtain the required information.

2.08.3.1 Estimating the Illuminant

In natural scenes, there are several indirect cues to illuminant color (Maloney, L. T., 2002). One is the spatial average of the colors in the scene, estimated visually by global mechanisms or by local mechanisms combined with eye movements (D'Zmura, M. and Lennie, P., 1986), or both. If the color gamut of the surfaces is sufficiently large, then their average should be chromatically neutral (the gray-world hypothesis: Evans, R. M., 1946/1951; Buchsbaum, G., 1980; Land, E. H., 1986), and any bias away from neutral should represent the illuminant color. Another indirect cue is the color of the highest-luminance surface in the scene. As it reflects the most light, it is most likely to be white or specular, and therefore any bias should represent the illuminant color (the bright-is-white hypothesis: Land, E. H. and McCann, J. J., 1971; Gilchrist, A. *et al.*, 1999). These two cues normally covary, but when pitted against each other, the spatial-average cue seems to dominate the highest-luminance cue, except when the scene has few surfaces (Linnell, K. J. and Foster, D. H., 2002).

Mutual illumination (Bloj, M. G. *et al.*, 1999) and specularities with nonuniform surfaces (Yang, J. N. and Maloney, L. T., 2001) may also be used to infer the scene illuminant, and, over a limited region, luminance-color correlations (Golz, J. and MacLeod, D. I. A., 2002; Granzier, J. J. M. *et al.*, 2005) may be used in a similar way.

2.08.3.2 Color Contrast and Variance

The cues to the scene illuminant provided by the spatial average and the brightest surface or specularities represent two spatial extremes in sampling the visual environment. The influence of more intermediate-range sampling is found in the classical color-contrast or chromatic-induction effects whereby the hue of a stimulus is shifted away from that of a surround field. These effects may be interpreted as local illuminant compensation (Hurlbert, A. and Wolf, K., 2004), being limited to about 1° of visual angle from the point of gaze (Brenner, E. *et al.*, 2003, see also Barbur, J. L. *et al.*, 2004), although some modulatory effects on color appearance may extend to 10° of visual angle (Wachtler, T. *et al.*, 2001).

Other spatial factors influencing color appearance in variegated scenes include differences in texture, which weaken chromatic-contrast induction (Hurlbert, A. and Wolf, K., 2004), and chromatic variation in a background field: areas appear more vivid and richly

colored against low-contrast, gray surrounds than against high-contrast, multicolored surrounds (Brown, R. O. and MacLeod, D. I. A., 1997; Shevell, S. K. and Wei, J., 1998; Brenner, E. and Cornelissen, F. W., 2002; Brenner, E. *et al.*, 2003).

2.08.3.3 Spatial Ratios of Cone Excitations

Unlike color constancy, relational color constancy (Section 2.08.2.3) does not require an estimate of the illuminant on the scene. In fact, the spatial ratios of cone excitations generated in response to light reflected from pairs of surfaces or groups of surfaces may provide sufficient cue to the stability or otherwise of surface color. As already noted (Section 2.08.2.2), such ratios have the property of being almost exactly invariant under changes in illuminant, both with artificial scenes of colored papers (Foster, D. H. and Nascimento, S. M. C., 1994) and with natural scenes (Nascimento, S. M. C. *et al.*, 2002), as illustrated in Figure 4 for long-, medium-, and short-wavelength cones in turn.

In theory, temporal ratios of cone excitations may also be calculated with similar effect. Eye movements back and forth across an edge separating different surfaces could define a ratio signal over recent time that, like spatial ratios, is almost exactly invariant under changes in illuminant. In making surface-color matches across two simultaneously presented Mondrian-like images, experimental observers switch gaze between test and reference surfaces with increasing frequency just before a match is made (Cornelissen, F. W. and Brenner, E., 1995). Spatial (and temporal) ratios may also be calculated across postreceptoral combinations (Zaidi, Q. *et al.*, 1997); across spatial averages of cone excitations (Amano, K. and Foster, D. H., 2004); and across the two eyes, suggesting the involvement of binocularly driven processes (Nascimento, S. M. C. and Foster, D. H., 2001; Barbur, J. L. *et al.*, 2004; see also Section 2.08.7.2).

The invariance or otherwise of these ratios may explain performance in several color-vision tasks (Westland, S. and Ripamonti, C., 2000; Ripamonti, C. and Westland, S., 2003; Foster, D. H. *et al.*, 2001b), including asymmetric color matching (Tiplitz Blackwell, K. and Buchsbaum, G., 1988). The calculation of ratios is a general device, which need not be restricted to primate or indeed vertebrate vision (Section 2.08.7). Bumblebees appear to make similar calculations to encode contrast relations between distinct elements of complex scenes (Lotto, R. B. and Wickelmaier, M., 2005).

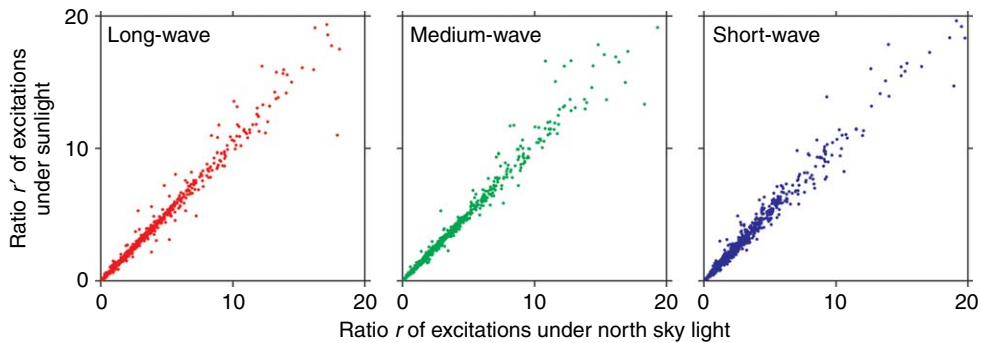


Figure 4 Scatterplot of ratios of cone excitations for long-, medium-, and short-wavelength-sensitive cones. Each point represents a pair of ratios r and r' of excitations in a cone class produced by light from a pair of surfaces drawn at random from a set of 25 natural scenes under, respectively, north sky light and sunlight, with correlated color temperatures 25 000 K and 4000 K. The mean deviation of pairs of ratios from equality is about 5% (see Foster, D. H. and Nascimento, S. M. C., 1994; Nascimento, S. M. C. *et al.*, 2002). Number of points in each graph is approximately 2400.

As illustrated earlier (Section 2.08.2.3, Figure 3), the cue provided by spatial cone-excitation ratios, unlike the scaling of cone responses defined by von Kries adaptation, has the advantage that it allows the separation of judgments about the stability of surface colors from judgments about the color of the illumination, which, environmentally, may be equally important (Jameson, D. and Hurvich, L. M., 1989).

2.08.4 Measuring Perceived Surface Color

Given that with one cue or another it is possible to estimate surface color from the light reflected from a scene, how is the ability to make this estimate assessed experimentally in the laboratory? There are four main methods of measurement, each of which is limited in different ways (Foster, D. H., 2003).

2.08.4.1 Color Naming and Scaling

The most direct approach to measuring color constancy is to test the consistency of color naming under different lights. Although certain color terms are basic (Berlin, B. and Kay, P., 1969; Uchikawa, K. and Boynton, R. M., 1987), observers may be given a free choice; for example, if they call an intense yellow surface cadmium yellow under one illuminant, do they use the same name under a different illuminant? In practice, however, even when the illuminant is constant, observers use the same name for other shades of intense yellow. The problem is that there are many

more distinguishable surface colors, perhaps more than two million (Pointer, M. R. and Attridge, G. G., 1998), than can be named accurately or consistently.

It is possible to increase the precision of color naming by adjoining a numerical scale, although the system is then no longer purely categorical (Foster, D. H., 2003). For example, observers may be asked to judge how red, green, blue, and yellow a test patch appears on a fixed scale of numbers (Schultz, S. *et al.*, 2006).

2.08.4.2 Setting Unique Hues

In contrast with color names in general, the so-called unique hues red, green, blue, and yellow can be set by an experimental observer precisely (Valberg, A., 1971). Surface-color judgments under different illuminants may then be measured by finding a color setting that excludes the other hues: a yellow test stimulus, for example, is set so that it is neither reddish nor greenish (Arend, L. E., 1993; Shevell, S. K. and Wei, J., 1998). But the method is necessarily limited to these four hues.

2.08.4.3 Achromatic Adjustment

Setting a color to neutral is the logical intersection of setting unique hues: a white or gray test surface is adjusted so that it appears neither reddish nor greenish nor bluish nor yellowish. Although used to measure color constancy, achromatic adjustment strictly records only the observer's estimate of local illuminant color. But by measuring the bias of this estimate, it may be used to probe the effects of scene

structure such as local chromatic context (Brainard, D. H., 1998; Kraft, J. M. and Brainard, D. H., 1999) and to reveal the role of memory in surface-color judgments (Smithson, H. and Zaidi, Q., 2004; Hansen, T. *et al.*, 2006).

2.08.4.4 Asymmetric Color Matching

Color naming and setting unique hues both involve color identification, but asymmetric color matching does not. Rather, it simply requires a match to be made between a test and a reference surface under different lights (Wyszecki, G. and Stiles, W. S., 1982). For example, with the lower left and right images of Figure 3, an experimental observer would adjust the color of the (initially gray) test sphere in the right scene under the mixture of sunlight and north sky light so that it appears to have the same color as the (blue) sphere in the left scene under sunlight. The scenes may be viewed simultaneously or sequentially. This surface-color match is also referred to as a paper match (Arend, L. and Reeves, A., 1986), owing to its association with test samples taken from the Munsell Book of Color (Munsell Color Corporation, 1976).

Color matching ensures only the equivalence of two stimuli, not necessarily that they produce the same color percepts (Foster, D. H., 2003). In principle, observers need judge merely whether the relation between the color of one surface in the scene and the color of one or more others is the same as when the scene is viewed under a different illuminant; in other words, whether relational color constancy holds (Section 2.08.2.3). Estimating the illuminant seems to be unnecessary, as reliable surface-color matches are possible with minimalist scenes of just two surfaces, which provide little information about the illuminant (Tiplitz Blackwell, K. and Buchsbaum, G., 1988; Arend, L. E. *et al.*, 1991; Amano, K. and Foster, D. H., 2005).

2.08.4.5 Discriminating Illuminant from Reflectance Changes

A completely operational approach to measuring surface-color perception is to ask observers to distinguish between illuminant and surface-reflectance changes in a scene (Craven, B. J. and Foster, D. H., 1992; Nascimento, S. M. C. and Foster, D. H., 1997; Zaidi, Q., 2001). Performance in one such task has been found to be fast, accurate, and effortless, suggesting the spatially parallel detection of deviations from constancy in spatial cone-excitation ratios over the visual field (Foster, D. H. *et al.*, 2001b).

2.08.5 Levels of Color Constancy

The methods of measuring surface-color perception outlined in Section 2.08.4 vary in the kinds of information they provide. For accurate results, it is important to have a criterion that refers implicitly or explicitly to surface color; otherwise, other aspects of color appearance may determine performance.

2.08.5.1 Dual Representations

When experimental observers are asked to match a test surface for hue and saturation (e.g., the sphere in the upper left and right images of Figure 3), the level of color constancy obtained is much poorer than when they are asked to make a paper match. One explanation (Arend, L. and Reeves, A., 1986) of these different levels has been based on the roles played by two kinds of constancy process, which have already been mentioned (Section 2.08.2).

In one process, the eye becomes accustomed to the new illuminant with both light adaptation (von Kries, J., 1905; Whittle, P., 1996) and contrast adaptation (Webster, M. A. and Mollon, J. D., 1995; Brown, R. O. and MacLeod, D. I. A., 1997). Mechanisms with multiple time courses may be involved (Fairchild, M. D. and Reniff, L., 1995; Rinner, O. and Gegenfurtner, K. R., 2000). As hue and saturation are preserved under the change in illuminant, a paper that looks unique yellow under direct sunlight would continue to look unique yellow under, say, the greenish light reflected or transmitted beneath a tree. In the other process there is little opportunity for this adaptation, as when the eye moves over a scene patterned by light and shade (Zaidi, Q. *et al.*, 1997). Hue and saturation change when the illuminant changes, but they are interpreted as resulting from constant surface colors – constant spectral reflectances – under varying illumination. The paper that looks unique yellow under direct sunlight would in fact look greenish-yellow under a tree but be clearly identifiable as yellow paper. The differences in the completeness of these two processes affect the level of color constancy achieved in the two kinds of task (Bäuml, K.-H., 1999; Logvinenko, A. D. and Maloney, L. T., 2006).

2.08.5.2 Role of Task and Stimulus

On a continuous scale in which perfect color constancy is 1 and perfect inconstancy 0 (Arend, L. E. *et al.*, 1991), average levels of constancy have, depending on task

and stimulus, been reported as 0.79–0.87 for asymmetric color matching in computer-simulated images of flat Mondrian-like patterns of different colored Munsell papers (Bäumel, K.-H., 1999; Foster, D. H. *et al.*, 2001a); 0.61 for asymmetric matching of real Munsell papers (Brainard, D. H. *et al.*, 1997) and 0.82 for achromatic adjustment of a test surface in an array of real Munsell papers (Brainard, D. H., 1998); 0.83 for achromatic adjustment of a test surface in a three-dimensional geometric tableau (Kraft, J. M. and Brainard, D. H., 1999); 0.70 for hue scaling of a test patch in a computer-simulated three-dimensional geometric tableau (Schultz, S. *et al.*, 2006); and 0.86 for asymmetric matching of a test object in a real three-dimensional geometric tableau (de Almeida, V. M. N. *et al.*, 2004) and 0.80 for discriminating illuminant from reflectance changes with similar stimuli (Nascimento, S. M. C. *et al.*, 2005a).

These constancy indices represent sometimes large variations across individual observers and stimuli, but systematic stimulus effects are identifiable. For example, with images of rural and urban scenes, 70% of the total variance in constancy indices can be explained by a combination of spatially averaged differences in spatial cone-excitation ratios, chroma, and hue (Foster, D. H. *et al.*, 2006a). Interestingly, three-dimensional scenes and natural scenes seem to provide no special advantage over flat and artificial scenes in eliciting high levels of constancy.

2.08.6 Color Appearance in Natural Environments

The abstract geometric displays used in laboratory measurements of color appearance usually have large, uniformly distributed color gamuts. By contrast, surfaces in natural scenes have smaller, more biased gamuts.

2.08.6.1 Colors of Natural Surfaces

The distribution of chromaticities of surfaces in natural scenes is dominated by browns, greens, and blues, from earth, vegetation, and sky (Hendley, C. M. and Hecht, S., 1949; Burton, G. J. and Moorhead, I. R., 1987; Osorio, D. and Bossomaier, T. R. J., 1992; Webster, M. A. and Mollon, J. D., 1997). More detailed analysis of these spectra suggests that the spectral positions of the long- and medium-wavelength-sensitive pigments (Figure 1) are optimal for primates discriminating ripe fruit or young leaves against a background of mature foliage

(Sumner, P. and Mollon, J. D., 2000; Dominy, N. J. and Lucas, P. W., 2001; Lucas, P. W. *et al.*, 2003), but color vision is also important more generally for identifying objects and surfaces in variegated environments (Chiao, C.-C. *et al.*, 2000; Osorio, D. and Vorobyev, M., 2005). The fact that metamerism (Section 2.08.1.1) is rare in natural scenes (Foster, D. H. *et al.*, 2006b) suggests the sufficiency of trichromatic vision, that is, more cone classes are unnecessary.

2.08.6.2 Discriminating and Identifying Natural Surfaces

How well does color appearance allow us to identify objects in natural scenes under different illuminants? Performance depends not only on color constancy but also on other factors, such as the number of different colored surfaces present that might act as distractors. For example, if just two surfaces are sampled, there is little risk of confusion with a change in lighting: their color appearance will generally be different, and this difference will persist when the illuminant changes. But as the number of surfaces increases, the risk of confusion increases.

The success of color-appearance models (Sections 2.08.1.4 and 2.08.2.2) in predicting object identification in natural scenes under different illuminants can be quantified in a quite general way by applying methods from information theory (Cover, T. M. and Thomas, J. A., 1991). For any particular model, the magnitude of the information preserved from a scene varies surprisingly little from scene to scene, suggesting that the sensory coding of surface color in natural scenes can be optimized independent of viewing direction for any particular range of illuminants (Foster, D. H. *et al.*, 2004).

2.08.7 Physiological Mechanisms

Color appearance is the product of multiple stages of processing in the visual system (Walsh, V., 1999; Hurlbert, A. and Wolf, K., 2004), but its precise neural basis remains unresolved, partly because of different experimental criteria used to assess it, as indicated earlier.

2.08.7.1 Processing in Retina and Lateral Geniculate Nucleus

Significant chromatic adaptation takes place retinally. Microelectrode recordings from monkey horizontal

cells have shown that, consistent with the von Kries scaling hypothesis, adaptation is cone-specific at moderate light levels, although it is also incomplete and necessarily spatially local (Lee, B. B. *et al.*, 1999). Recordings from goldfish, which can make color-constant judgments (Neumeyer, C. *et al.*, 2002), have indicated that cone synaptic gains are modulated by the horizontal cell network in such a way that the ratios of cone outputs are almost invariant with the illuminant spectrum (Kraaij, D. A. *et al.*, 1998; Kamermans, M. *et al.*, 1998). Normalizing shifts in chromatic sensitivity have also been found in monkey parvocellular lateral geniculate neurons and their retinal afferents (Creutzfeldt, O. D. *et al.*, 1991).

A retinal contribution has also been revealed in humans by functional magnetic resonance imaging (Wade, A. R. and Wandell, B. A., 2002) and in subjective reports of color-induction in hemianopia (Pöppel, E., 1986).

2.08.7.2 Cortical Processing

A potential basis for the cortical calculation of spatial cone-excitation ratios is provided by double-opponent cells, which have been found in area V1 of the monkey visual cortex and which are sensitive to spatial chromatic contrast (Conway, B. R., 2001; Conway, B. R. and Livingstone, M. S., 2006). These cells are probably different from those cells in V1 that respond strongly to homogenous colored patches on large backgrounds (Wachtler, T. *et al.*, 2003) and which may contribute to chromatic-induction effects found in humans (Wachtler, T. *et al.*, 2001), including, the effect of colored patches remote from the test stimulus (Section 2.08.3.2).

Asymmetric color matching and color naming by patients with lesions higher than V1 also suggest that chromatic-contrast effects are calculated in area V1 or lower (Hurlbert, A. and Wolf, K., 2004). One patient with cerebral achromatopsia, despite being unable to match or name surface colors, was found able to discriminate changes in spatial cone-excitation ratios with simple scenes, but not with complex ones, suggesting a failure of integrative processes over the visual field (Hurlbert, A. C. *et al.*, 1998; see also Kentridge, R. W. *et al.*, 2004; Barbur, J. L. *et al.*, 2004).

Reminiscent of Land's experiments with Mondrian-like displays (Land, E. H., 1959a), cells in area V4 of the monkey visual cortex have been found to respond to a red patch when an entire multicolored Mondrian pattern was illuminated by long-, medium- and short-wavelength lights, but not with long-wavelength light

alone (Zeki, S., 1980). Conversely, with lesions to V4, monkeys experience difficulty in identifying a colored surface under different illuminants (Walsh, V. *et al.*, 1993), and patients with lesions to the lingual and fusiform gyri, which include part of putative human area V4, have deficits in surface-color perception (Kennard, C. *et al.*, 1995; Clarke, S. *et al.*, 1998). Color constancy can also be selectively impaired after circumscribed unilateral lesions in parieto-temporal cortex (Rüttiger, L. *et al.*, 1999).

2.08.7.3 Inherited Color-Vision Deficiency

The abnormalities of inherited color-vision deficiency are evident on traditional clinical color-vision testing. Yet red-green dichromats, protanopes and deuteranopes, who have, respectively, no long- and medium-wavelength-sensitive pigments (Deeb, S. S., 2004), are able to identify surface colors under a fixed illuminant (Cole, B. L. *et al.*, 2006). They can also make achromatic settings (Rüttiger, L. *et al.*, 2001) and discriminate reflectance changes from illuminant changes with Mondrian-like patterns under different illuminants (Baraas, R. C. *et al.*, 2004), although their performance, and that of tritanopes (Foster, D. H. *et al.*, 2003), who have no short-wavelength-sensitive pigment, may be more variable and poorer than that of normal controls.

Deuteranomalous trichromats, whose medium-wavelength-sensitive pigment is replaced by a pigment closer to the long-wavelength-sensitive pigment (Deeb, S. S., 2004), can discriminate random reflectance changes from illuminant changes in natural scenes about as well as normal trichromats can (Baraas, R. C. *et al.*, 2006). Protanomalous trichromats, whose long-wavelength-sensitive pigment is replaced by a pigment closer to the medium-wavelength-sensitive pigment, perform somewhat less well.

The reasons for these variations in performance are incompletely understood. Possible explanatory factors include the influence of rod signals at lower light levels; the availability of cues from spatial ratios of cone excitations or of opponent combinations of cone excitations with altered spectral coverage; differences between stimuli based on natural and artificial reflectance spectra; and, for dichromats, the direction in chromaticity space of the loci of indistinguishable colors relative to the direction of the illuminant change. In general, however, individuals with color-vision deficiency may be less disadvantaged in judging natural surface colors than might be expected from clinical color-vision data.

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