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The Perceptual Organization of Colors: An Adaptation to Regularities of the Terrestrial World?

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Those taking an evolutionary approach to the behavioral, cognitive, and social sciences have been emphasizing the natural selection of mechanisms and strategies that are specific to particular species, genders, and problem domains. This emphasis on the particular is understandable as a reaction against the tendency, long dominant in these sciences, to proceed as if human and animal behavior could be explained in terms of just two things: (a) general laws of learning and cognitive constraints that hold across species, genders, and domains, and (b) the particular set of environmental (including cultural) circumstances to which each animal can adapt only by learning through its own individual experience. Evolutionary theorists' emphasis on specific adaptations may also reflect the tendency of such adaptations to catch our attention through the very diversity of their specificity. Adaptations to universal features of our world are apt to escape our notice simply because we do not observe anything with which such adaptations stand in contrast.

In this chapter I consider some characteristics of the perception and representation of colors that, although not universal in animal vision, do appear to be universal in the normal color vision of humans, prevalent in other primates, and common in a number of other quite different but also highly visual species, including the birds and the bees. The questions raised are (a) whether these characteristics of color perception and representation are merely arbitrary design features of these particular species, (b) whether these characteristics arose as specific adaptations to the particular environmental niches in which these species evolved, or (c) whether they may have emerged as advanced adaptations to some properties that prevail throughout the terrestrial environment. My discussion here will principally concern four remarkable characteristics of the colors that we so immediately and automatically experience when we look at the objects around us.

1. *The perceptual constancy of colors.* Opening our eyes seems like simply opening a window on a surrounding world of enduring objects and their inherent colors. Closer consideration shows, however, that our experience of the colors of objects depends on a process of visual analysis that, although largely unconscious, must be highly sophisticated and complex. Because most terrestrial objects do not shine by their own light, the light that strikes our eyes from those objects and by which we see them generally originates in a very different, extraterrestrial source—namely, the sun. Moreover,

depending on the circumstances in which an object is viewed, that solar illumination is subject to great variation in spectral composition. For example, light striking an object directly from an overhead sun may be strongest in middle wavelengths (yellows), light scattered to an object from clear sky may be strongest in short wavelengths (blues), and light from a setting sun may be strongest in long wavelengths (reds). Depending on such viewing conditions, the light scattered back to our eyes from any given object can accordingly be strongly biased toward the middle, shorter, or longer wavelengths and, so, toward the yellows, blues, or reds. Yet, despite these great variations in the light that a surface scatters back to our eyes under these different conditions, the color that we perceive a surface to have remains a fixed, apparently inherent property of the surface itself.

The adaptive significance of such perceptual constancy of surface color is clear. In order to respond appropriately to an object we must recognize it as the same distal object despite wide variations in the illumination and in the resulting composition of the light striking our retinas. After centuries of investigation, the question of how our visual systems achieve color constancy has been considerably clarified and, perhaps, essentially answered (see Maloney & Wandell, 1986). Although the principle of color constancy underlies virtually everything I have to say in this chapter, that principle (if not yet the specific physiological mechanism by which it is achieved) has long been accepted as fundamental in psychology and visual science. To the extent that I have any new ideas to present, these will primarily concern the following three other characteristics of human color perception and representation—characteristics that, although well established, still have no generally accepted explanations.

2. *The three-dimensional structure of colors.* In terms of its chromatic composition, the light reaching our eyes from any one point in the visual field can vary in an unlimited number of dimensions. Each such dimension would specify the amount of energy in the light that is of one particular wavelength within the range of visible wavelengths—between about 400 nm (nanometers) at the violet end of the visible spectrum and about 700 nm at the red end. Yet the surface colors experienced by humans with normal color vision (in addition to being essentially constant for each surface) vary between different surfaces in only three dimensions (Helmholtz, 1856–1866; Young, 1807). In operational terms, normal observers can match the color appearance of any given surface by adjusting three—but no fewer than three—knobs on a suitable color-mixing apparatus.

Accordingly, the surface colors experienced by normally sighted human observers are representable as points in a three-dimensional *color space,* whose three dimensions can be taken to be those called *lightness, hue,* and *saturation* (see Figure 13.1a). Why is the number of dimensions of our representation of colors exactly three—rather than, say, two or four? Furthermore, given that we experience colors as properties of the surfaces of external objects, in what sense, if any, does this three-dimensionality of our color experience reflect a three-dimensionality in the world?

3. *The circular structure of spectrally pure colors.* The colors that correspond to the hues of the rainbow—chromatically pure colors that are maximally saturated in the sense that they differ as much as possible from a (correspondingly light, medium, or dark) neutral or achromatic gray—can each be matched by light that is spectrally pure, that is, composed of a single wavelength. (The only saturated colors that cannot be matched by a single wavelength are the purples, which arise from mixtures of a long-wavelength red and a short-wavelength blue or violet.) Given that the pure colors of

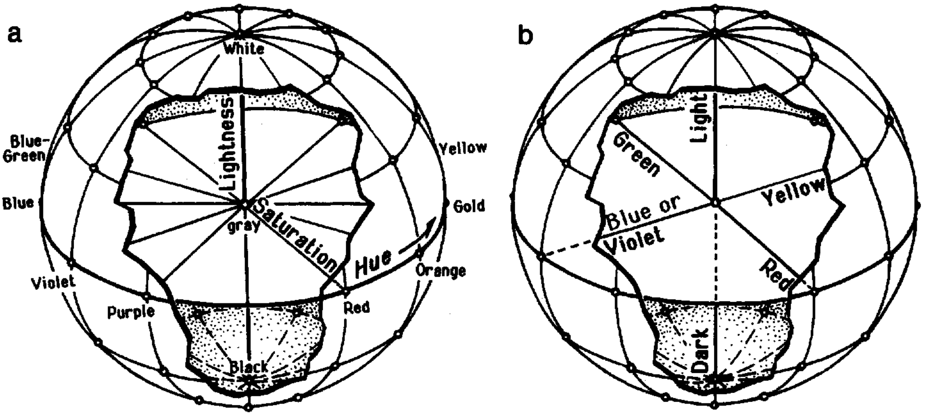

Figure 13.1 Schematic representations of three-dimensional color space in terms of three polar dimensions of lightness, hue, and saturation (a) or in terms of three dimensions of opponency between lightness versus darkness, blueness versus yellowness, and redness versus greenness (b).

the rainbow thus correspond to a single physical dimension (wavelength), it is not surprising that these colors are represented by a single dimension of three-dimensional color space—namely, the dimension we call *hue.* What does need explaining, is why this dimension of hue is not rectilinear, like the physical dimension of wavelength to which it corresponds, but circular (as schematically illustrated by the equatorial line around color space in Figure 13.1a).

The circular representation of hue, originally described by Isaac Newton (1704) and accordingly referred to as *Newton's color circle,* is entailed by an elementary perceptual fact: The hues at the two ends of the physical continuum of visible wavelengths—namely, long-wavelength red and short-wavelength violet—are experienced by individuals with normal color vision as more similar to each other than either is to intermediate-wavelength green. This psychological proximity between the physically most widely separated (red and violet) ends of the hue continuum can be achieved in color space only by bending this continuum into a circle. Is this circularity of hue a manifestation of an arbitrary characteristic of our perceptual system, then? Or might it have some deeper source, if not simply in the wavelengths of spectrally pure lights, in some more subtle regularity of the physical world?

4. *The universal organization of colors into categories and prototypes.* The three-dimensional space of surface colors (Figure 13.1)—including the one-dimensional circle of hues around the perimeter of that space—is continuous in the sense that between any two distinctly different colors, we can obtain, by color mixing, a color of intermediate appearance. At the same time, however, this continuous space seems to divide into relatively discrete regions within which the colors appear relatively more homogeneous than colors that cross the boundaries between such regions. Within such a region, moreover, the colors tend to be described by a single basic color word, such as our English words "red," "yellow," "green," or "blue." With even greater consistency, we generally agree with each other about what highly localized subregion within each such general region contains the best or most prototypical examples of the color prevailing throughout that general region.

Indeed, across human cultures, regardless of the duration and distance of their geographical separation and the number of basic color terms that their very different languages include, there seems to be a universal underlying hierarchy of regions and, especially, prototypical subregions of color space to which native speakers assign whatever basic color terms their individual languages include (Berlin & Kay, 1969). Thus, most languages have terms that native speakers apply to colors in the very same regions of color space for which we use the words "red" and "green." If, in addition, a given language also includes words corresponding (for example) to our "orange" or "purple," those word, too, are applied to essentially the same regions of color space for which we use "orange" or "purple." There is, moreover, especially great consistency in the locations of the colors that are picked out as the best or purest example of any particular color. Is this categorical organization of human color representation the manifestation of an arbitrary design feature of the human visual system? Or, again, is it a reflection of some general property of the world?

I do not claim to have final and definitive answers for these last three questions—concerning the three-dimensionality of colors, the circularity of hues, and the consistent organization of colors into categories and prototypes. Believing, however, that these questions are worth exploring from an evolutionary standpoint, I shall tentatively propose some hypotheses as to where in the world we might look for pervasive and enduring regularities to which these structural properties of the human visual system may have accommodated through natural selection. First, however, I attempt to situate my proposals within the broader context of human perceptual and cognitive constraints generally.

STRUCTURE IN HUMAN PERCEPTION AND COGNITION IN GENERAL

For over a century, psychological researchers have been probing the structures and processes of perception, memory, and thought that mediate the behaviors of humans and other animals. Typically, this probing has taken the form of behavioral experiments suggested by evidence from one or more of three sources: (a) introspections into one's own experience and inner processes, (b) information gleaned about the anatomy or physiology of the underlying physical mechanisms, and (c) results obtained from previous behavioral studies. More recently, in seeking to understand not only the nature but also the origins of psychological principles, some of us have been turning to a fourth source for guidance—namely, to the ecological properties of the world in which we have evolved and to the advantages to be realized by individuals who have genetically internalized representations of those properties.

Taken by themselves, findings based on introspective, behavioral, and physiological evidence alike, however well established and mutually consistent they may be, remain as little more than "brute facts" about the human or animal subjects studied. What such findings reveal might be merely arbitrary or ad hoc properties of the particular collection of terrestrial species investigated. Even our own perceptual and cognitive capabilities, as much as our own bodily sizes and shapes, may be the products of a history of more or less accidental circumstances peculiar to just one among uncounted evolutionary lines. Certainly, these capabilities do not appear to be wholly dictated by what is physically possible.

The following are just a few of the easily stated and well known of our perceptual/

cognitive limitations, as these have been demonstrated under highly controlled but nonnaturalistic laboratory conditions:

1. Although a physical measuring instrument can reliably identify a vast number of absolute levels of a stimulus, we reliably identify only about seven (Miller, 1956).
2. Although a physical recording instrument can register a vast number of dimensions of variation of the spectral composition of light, the colors we experience vary, as I have already noted, along only three independent dimensions (Helmholtz, 1856-1866; Young, 1807).
3. Although the red and violet spectral colors differ the most widely in physical wavelength, these colors appear more similar to each other than either does to the green of an intermediate wavelength (leading, as noted, to Newton's color circle).
4. Although a camera can record and indefinitely preserve an entire scene in a millisecond blink of a shutter, the "iconic" image that our visual system retains from a single brief exposure decays in less than a second and, during this time, we are able to encode only about four or five items for more permanent storage (Sperling, 1960).
5. Although a computer can store an essentially unlimited number of unrelated items for subsequent retrieval, following a single presentation, we can reliably recall a list of no more than about seven items (Miller, 1956).
6. Although a computer could detect correlations between events separated by any specified time interval and in either order of occurrence, in virtually all animals with nervous systems, classical conditioning generally requires that the conditioned stimulus last for a short time and either be simultaneous with the unconditioned stimulus or precede it by no more than a few seconds (Pavlov, 1927, 1928).
7. Although a computer can swiftly and errorlessly carry out indefinitely protracted sequences of abstract logical operations, we are subject to systematic errors in performing the simplest types of logical inferences (e.g., Tversky & Kahneman, 1974; Wason & Johnson-Laird, 1972; Woodworth & Sells, 1935)—at least when these inferences are not of the kind that were essential to the fitness of our hunter-gatherer ancestors during the Pleistocene era (Cosmides, 1989).

Our performance in a natural setting is, however, a very different matter. There, our perceptual and cognitive capabilities vastly exceed the capabilities of even the most advanced artificial systems. We readily parse complex and changing visual scenes and auditory streams into spatially localized external objects and sound sources. We classify those objects and sources into natural kinds despite appreciable variation in the individual instances and their contexts, positions, or conditions of illumination. We infer the likely ensuing behaviors of such natural objects—including the recognition of animals and anticipation of their approach or retreat, the recognition of faces and interpretation of their expressions, and the identification of voices and interpretation of their meanings. We recode and transfer, from one individual to another, information about arbitrary or possible states of affairs by means of a finite set of symbols (phonemes or corresponding written characters). And we plan for future courses of action and devise creative solutions to an open class of real-world problems.

To the extent that psychological science fails to identify nonarbitrary reasons or sources for these perceptual/cognitive limitations and for these perceptual/cognitive capabilities, this science will remain a merely descriptive science of this or that particular terrestrial species. This is true even if we are able to show that these limitations and capabilities are consequences of the structures of underlying neurophysiological mechanisms. Those neurophysiological structures can themselves be deemed nonarbitrary only to the extent that they can be seen to derive from some ultimately nonarbitrary source.

Where, then, should we look for such a nonarbitrary source? The answer can only be, "In the world." All niches capable of supporting the evolution and maintenance of intelligent life, though differing in numerous details, share some general—perhaps even universal—properties. It is to these properties that we must look for the ultimate, nonarbitrary sources of the regularities that we find in perception/cognition as well as in its underlying neurophysiological substrate.

Some of the properties that I have in mind here are the following (see Shepard, 1987a, 1987b, 1988, 1989): Space is three-dimensional, locally Euclidean, and endowed with a gravitationally conferred unique upward direction. Time is one-dimensional and endowed with a thermodynamically conferred unique forward direction. Periods of relative warmth and light (owing to the conservation of angular momentum of planetary rotation) regularly alternate with periods of relative coolness and darkness. And objects having an important consequence are of a particular natural kind and therefore correspond to a generally compact connected region in the space of possible objects—however much those objects may vary in their sensible properties (of size, shape, color, odor, motion, and so on).

Among the genes arising through random mutations, then, natural selection must have favored genes not only on the basis of how well they propagated under the special circumstances peculiar to the ecological niche currently occupied, but also, as I have argued previously (e.g., Shepard, 1987a), even more consistently in the long run, according to how well they propagate under the general circumstances common to *all* ecological niches. For, as an evolutionary line branches into each new niche, the selective pressures on gene propagation that are guaranteed to remain unchanged are just those pressures that are common to all niches.

Motivated by these considerations, much of my own recent work on perception and cognition in humans has sought evidence that our perceptual/cognitive systems have in fact internalized, especially deeply, the most pervasive and enduring constraints of the external world. In previous papers, I have primarily focused on evidence concerning two types of perceptual/cognitive capabilities: The first is our capability for representing rigid transformations of objects in three-dimensional Euclidean space—as revealed in experiments (a) on the perception of actually presented motions, (b) on the illusion of visual apparent motions, and (c) on the imagination of possible motions (Shepard, 1981, 1984, 1988; Shepard & Cooper, 1982; and, for a recent group-theoretic formulation, Carlton & Shepard, 1990). The second is our capability for estimating the conditional probability that a particular object is of the natural kind having some significant consequence, given that another particular object has already been found to have that consequence—as revealed in experiments on stimulus generalization and transfer of learning (Shepard, 1987b).

I turn now to the specific questions raised at the outset concerning four major characteristics of our perception and mental representation of surface colors—namely, their constancy, their three-dimensionality, their circularity with respect to hue, and their organization into categories and prototypes. In addition to reviewing the basic empirical phenomena to be explained in each case, I argue that these phenomena may arise not from merely accidental features of the human visual system but from genetic accommodations to identifiable regularities in the terrestrial world.

THE PERCEPTUAL CONSTANCY OF COLORS

Among the four major characteristics of human color perception mentioned, that of color constancy is undoubtedly of the most obvious and well-understood functional significance. This is not to say that the achievement of constancy is in any way trivial. The light that reaches our eyes from an external surface is a product of both the spectral reflectance characteristics of a surface and the spectral energy distribution of the light that happens to fall on that surface. In fact, as I shall shortly note, each of two surfaces can retain its own distinct color appearance even when the two surfaces are viewed under such different conditions of illumination that the light that each surface reflects back to our eyes is of identical composition. This could happen, for example, if a reddish object is illuminated solely by the bluish light of the sky, while a bluish object is illuminated solely by the reddish light of the setting sun. Constancy in the appearance of surfaces under such different conditions of illumination can be achieved only to the extent that the visual system can successfully infer the separate contributions—of the surfaces and of the lighting—that have jointly given rise to the retinal stimulus.

By what mechanism does the visual system make such an inference and, hence, attain constancy in the perceived colors of objects? Two computational theories of color vision have been especially influential in the development of my own thinking about a possible evolutionary basis for the way in which humans represent colors. The first was the *retinex* theory proposed by Edwin Land (1964). Although that theory turns out to provide an incomplete solution to the problem of color constancy, it first suggested to me that the principal features of color vision may have arisen as an accommodation to regularities in the world. The second is the general linear model for color vision more recently put forward by Maloney and Wandell (1986). In addition to providing what I take to be the first satisfactory solution to the problem of color constancy, this model finally led me to an evolutionary argument as to why human vision should be trichromatic, that is, should have exactly three dimensions of color representation.

Land's Retinex Scheme for Color Constancy

The possibility that the subjective phenomena of color may reflect an objective property of the world began to intrigue me on attending Land's strikingly illustrated William James Lectures, at Harvard University in 1967, on his *retinex theory* (see Land, 1964, 1986). Previously, textbook accounts of color vision had focused on phenomena attributable to peripheral, often retinal, sensory mechanisms. Principal examples of such phenomena are the gradual adjustment of visual sensitivity, called *adaptation,* following a change in general level of illumination, and the illusory shift in appearance of a surface (toward the lighter or darker, redder or greener, bluer or yellower), called *simultaneous* or *successive contrast,* when that surface is surrounded or preceded by a surface that is, contrastingly, darker or lighter, greener or redder, yellower or bluer, respectively. (Such phenomena of adaptation and contrast, incidentally, are characteristic of most sensory mechanisms and not specific to color or even to vision.) A major thrust of Land's approach, conditioned perhaps by his practical interest in contributing to color photography, was to look beyond the sensory mechanisms to the world outside and to consider the problem that the world presents and that the sensory mechanisms must solve. This is essentially the approach taken to vision in general by David Marr (1982) and, originally (but without the goal of also developing a computational model), by James Gibson (1950, 1966, 1979).

Land's demonstrations showed, in a particularly compelling way, that the color that we experience of a patch of surface is not determined by the composition of the light reaching our eyes from that patch. Instead, the color we experience somehow captures an invariant property of the surface itself, despite the enormous illumination-contingent variations in the composition of the light reflected back to our eyes. For example, Land illuminated a large display composed of rectangular sheets of many different colored papers (called a "Mondrian" because it resembled the abstract paintings by Mondrian) by means of three projectors—one projecting short-wavelength (violet) light, one projecting middle-wavelength (green) light, and one projecting long-wavelength (red) light. The intensity of the colored light from each projector could be independently controlled. On a screen above the Mondrian display, the projected image of the dial of a telescopic spot photometer registered the intensity of the light reflected back from any rectangular patch in the Mondrian at which the photometer was currently pointed.

With one setting of the intensities of the three illuminating projectors, Land pointed the spot photometer at a patch of the Mondrian that appeared a rust-colored reddish brown. In turn, pairs of the three projectors were turned off, and, from the projected image of the dial of the spot photometer, we could see how much light from the successively isolated short-, middle-, and long-wavelength projectors was being reflected back to our eyes from that rust-colored patch. Next, Land pointed the spot photometer at a very different, green patch. Again, all pairs of the three projectors were successively turned off (yielding, of course, very different readings of the amounts of short-, middle-, and long-wavelength light reflected from this green patch). The intensity of each projector was then adjusted so that according to the spot photometer, the very same amount of light from that projector—when it alone remained on—was reflected back to our eyes by the green patch as had previously been reflected back (from that projector) by the reddish brown patch. For example, in order to get the same amount of red light reflected back from the green patch as had previously been reflected back from the reddish brown patch, the red projector had to be turned way up; and in order to get the same amount of green light reflected back, the green projector had to be turned way down.

As a result of these adjustments, when all three projectors were then turned back on, our eyes were receiving light from the green patch that was virtually identical in physical composition to the light our eyes had previously been receiving from the reddish brown patch. Astonishingly, under this greatly altered lighting the originally reddish brown patch still appeared reddish brown, and the originally green patch still appeared green! In fact, the entire Mondrian display appeared essentially unchanged. Clearly, color is in the eye of the beholder in the sense that it does not have a one-to-one correspondence to the physical composition of the light that, striking the retina, gives rise to that color (or even, as we shall see, to the dimensionality of the variations that occur in that composition). Yet the resulting subjective experience of color, evidently, does capture an invariant property of the surface of the distal object.

Land proposed his retinex theory to account for this remarkable feat of color constancy by positing that the visual system automatically computes an independent brightness normalization within each of three color channels (which, for present purposes, we can think of as associated with the short-, middle-, and long-wavelength receptors). In effect, he assumed that the gain of each chromatic channel is increased or reduced so that the output for that channel, when that output is integrated over the entire visible scene, maintains a fixed, standard level of lightness. Thus, when the relative amount of long-wavelength light in the illumination increases—whether because the intensity of a red projector is turned up or because the sun is setting—there is a correlated increase in the amount of red light reflected from the scene as a whole. But the visual system automatically compensates for this increase in the average redness of the light reflected back from the entire scene by decreasing in the overall gain of the long-wavelength input channel. The consequence is that the scene (including a reddish brown patch and a green patch) continues to look essentially the same.

Land's approach to color vision appealed to me because it pointed toward the possibility that fundamental aspects of color vision may not be by-products of accidental design features of the visual system arising in a particular species but may represent a functional accommodation to a quite general property of the world in which we and other terrestrial animals have evolved. Land himself suggested something of this sort when he spoke of our "polar partnership" with the world around us (Land, 1978).

Still, Land's retinex theory does not in itself provide an answer to the questions of why we have specifically three chromatic input channels and hence specifically three dimensions of color vision. Moreover, the retinex theory has been shown to fall short of providing a satisfactory account of color constancy itself. Normalization of lightness within each of three color channels independently will achieve color constancy only if the whole scene viewed includes a typical representation of short-, middle-, and long-wavelength-reflecting surfaces. If the scene is strongly biased toward the reds (as in a canyon in the southwestern U.S.), toward the greens (as in a rain forest), or toward the blues (as in a sky and water scene), the proposed normalization will strive to remove the overall red, green, or blue complexion of the light reflected back from the scene even though, in each of these cases, the complexion is an inherent characteristic of the scene itself and not a bias imposed by the currently prevailing illumination. Indeed, in photography and television, color rendering is similarly attempted by separately adjusting the intensities of each of three color channels—with results whose inadequacies are all too familiar.

Maloney and Wandell's General Linear Model for Color Constancy

Building on work by Sälström (1973), Brill (1978; Brill & West, 1981; West & Brill, 1982), Buchsbaum (1980), and others, Laurence Maloney and Brian Wandell more recently put forward a general linear model for color vision that overcomes the principal limitations of Land's retinex theory (Maloney & Wandell, 1986). It was the advent of Maloney and Wandell's model at Stanford University that finally (nearly 20 years after Land's William James Lectures) suggested to me the possibility, to which I will soon turn, of a nonarbitrary basis for the three-dimensionality of human color vision.

Maloney and Wandell's theory does not require the restrictive assumption that the distribution of intrinsic colors in each scene always be the same. In their model, surface colors are estimated by applying a transformation to all three chromatic channels jointly, rather than to each channel separately. The resulting general linear transformation yields estimates of the intrinsic surface colors that approximate invariance both under natural variations of illumination and under wide variations of the distribution of surface colors (such as arise in a red canyon, a green rain forest, or a blue sky and water scene). Although the mathematical formulation of Maloney and Wandell's model is not essential here, it is worth one paragraph and one equation for those who are able to appreciate its elegance and generality.

The three central components of the model specify the dependencies on wavelength of (a) the illumination falling on the scene, (b) the light-reflecting characteristics of the surfaces making up the scene, and (c) the light-absorbing characteristics of the light-sensitive receptors in the eye viewing the scene. Specifically, for each point x of a surface in the scene and for each wavelength of light λ, the three components are: *the spectral power distribution of the illumination,* a function of wavelength $E^x(\lambda)$ specifying the amount of light (e.g., in quanta per second) of each wavelength λ falling on the surface point x; *the spectral reflectance distribution of the surface,* a function of wavelength $S^x(\lambda)$ specifying the proportion of any light quanta of wavelength λ falling on the surface at point x that will be scattered back from that surface (rather than being absorbed by the surface); and *the spectral sensitivity characteristics of the photoreceptive units,* functions of wavelength $R_k(\lambda)$ giving, for retinal receptors (cones) of each type k the sensitivity of receptors of that type to light of wavelength λ. The response of a receptor of type k to light scattered from the point x on the surface is then given by integration of the product of these three components over the entire spectrum of wavelengths:

$$\rho_k^x = \int E^x(\lambda)S^x(\lambda)R_k(\lambda)\,d\lambda \qquad k = 1, 2, \ldots, N$$

(where, for humans, who have three types of cones, $N = 3$).

Crucial to the application of this model to the problem of color constancy is the evidence, reviewed by Maloney and Wandell (1986), that the first two of these functions of wavelength, $E^x(\lambda)$ and $S^x(\lambda)$, each have only a limited number of degrees of freedom in the natural environment. That is, although the functions characterizing individual conditions of illumination and individual physical surfaces can each take on a potentially unlimited number of different shapes, in the natural terrestrial environment each of these shapes can be approximated as some linear combination of a small number of fixed underlying functions, called the *basis lighting functions* and the *basis reflectance functions,* respectively. (For those familiar with factor analysis or principal components analysis, this is merely another instance of the way in which redundancies or correlations in multivariate data permit the approximate reconstruction of those data from a relatively small number of underlying factors.)

Thus, although the complete specification of the light-reflecting characteristics of a surface must give, for each wavelength of light striking that surface, the proportion of the light of that wavelength that will be scattered back from the surface (rather than being absorbed), for most naturally occurring surfaces the spectral reflectance distributions $S^x(\lambda)$ turn out to be smooth, well-behaved functions of wavelength (Barlow, 1982; Stiles, Wyszecki, & Ohta, 1977). There is, moreover, a well-understood physical reason for this in terms of the Gaussian smoothing entailed by the very large number of quantum interactions among numerous neighboring energy states in surface atoms that mediate the absorption and re-emission of incident photons (Maloney, 1986; Nassau, 1983). In any case, the smoothness and, hence, redundancy in the empirically obtained spectral reflectance functions permits these functions to be approximated as linear combinations of a few basis functions (Cohen, 1964; Krinov, 1947; Yilmaz, 1962)—although evidently not as few as three (Buchsbaum & Gottschalk, 1984; Maloney, 1986).

For natural conditions of lighting, on the other hand, spectral energy distributions $E^x(\lambda)$ apparently can be adequately approximated as linear combinations of just three basis lighting functions (Judd, McAdam, & Wyszecki, 1964; also see Das & Sastri, 1965; Dixon, 1978; Sastri & Das, 1966, 1968; Winch, Boshoff, Kok, & du Toit, 1966). For example, Judd et al. found that 622 empirically measured spectral power distributions, measured under a great variety of conditions of weather and times of day, could be accurately approximated as weighted combinations of just the three functions plotted in Figure 13.2. (As in factor analysis, these particular basis functions are not uniquely determined by the data. Other sets of three basis functions that differ from these by a nonsingular linear transformation, such as a rotation, would account for the data just as well. The important point is that whichever of the alternative basis functions are used, they must be three in number.)

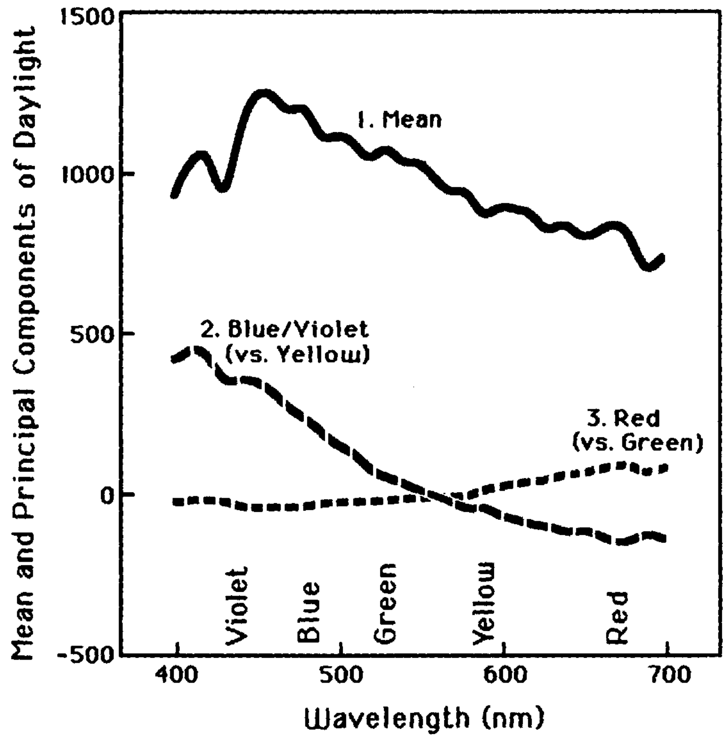

Figure 13.2 Three basis functions of wavelength that can be linearly combined to account for the major variations in the spectral compositions of natural daylight. (Based on Table 1 on page 1035 of Judd, MacAdam, & Wyszecki, 1964; copyright by the American Institute of Physics, 1964).

Maloney and Wandell (1986) showed that the unknown surface reflectance functions $S^x(\lambda)$—that is, the intrinsic colors of the surfaces—can be approximated, up to a *single* multiplicative scalar, solely from the responses of the N classes of photoreceptors, provided that two conditions are met: (a) The number of chromatically distinct classes of photoreceptors, N, must be one greater than the number of degrees of freedom of the surface reflectances; (b) the number of chromatically distinct visible surfaces in the scene viewed must be at least $N - 1$.

The single multiplicative scalar that remains indeterminate in Maloney and Wandell's model corresponds to an overall (achromatic) lightness that, according to the general linear model, cannot be unambiguously apportioned between the surfaces and the illumination falling on those surfaces. The light reflected from surfaces, alone, contains, in fact, insufficient information for any scheme of visual analysis to distinguish between darker surfaces under brighter lighting and corresponding but lighter surfaces under dimmer lighting. Maloney and Wandell nevertheless achieved a decisive advance by reducing the residual indeterminacy to a single scalar. Moreover, that single scalar can probably be adequately approximated, in most natural settings, by estimating the overall brightness of the illumination in ways not explicitly taken into account by the linear model (as originally framed solely in terms of the light scattered from surfaces). For example, the brightness of the illumination might be estimated, independently of the light scattered from surfaces, from the brightness of the sky (together with visual evidence for the presence of objects shading the surfaces viewed).

In contrast, Land's retinex model included not one but three indeterminate scalars—one for the overall lightness level within each of the three (red, green, and blue) chromatic channels. Brainard and Wandell (1986) have shown, further, that attempts to approximate surface color by correcting lightnesses within each chromatic channel separately, as in retinex schemes, rest on the unjustifiable assumption that the set of basis lighting functions $E^x(\lambda)$ can be chosen (by some linear transformation) so that variations in the weight of any one basis function affects the response of only one chromatic channel.

In fact, by striving for lightness constancy within each chromatic channel separately, retinex schemes necessarily forfeit not only constancy of colors, as such, but also constancy of the relative, purely achromatic lightnesses of different objects. In a chromatic world, even the ordering of recovered lightnesses within each channel will depend on the spectral balance of the illumination—unless the ability to see under dim illumination is seriously compromised by restricting each channel to a very narrow band of wavelengths. With broadly tuned and hence efficient channels (like those actually found in animals), a retinex system could estimate a patch of surface that reflects only shorter wavelengths to be either lighter or darker than a patch that reflects only longer wavelengths, depending on whether the illumination contains primarily shorter or longer wavelengths, respectively. This indeterminacy in the estimation of relative lightnesses of surfaces cannot be eliminated by any comparison between the outputs of separate channels, which, as in retinex schemes, each contain their own arbitrary multiplier. Such an indeterminacy can be eliminated only by transforming all three channels jointly, as advocated by Maloney and Wandell (1986).

I have gone into theories of color constancy at such length not only because color constancy is of obvious adaptive significance but also because I believe the mechanisms that have evolved for the achievement of color constancy may underlie the other major features of human color representation that I will be considering in the ensuing sections. If I am correct in this, these features, too, are not arbitrary but reflect pervasive and enduring regularities of the terrestrial environment in which we have evolved.

THE THREE-DIMENSIONALITY OF COLORS

The three-dimensionality of human color perception reveals itself, as I already noted, in the ability of a normally sighted observer to match the color appearance of any presented surface by adjusting three, but no fewer than three, unidimensional controls on a suitable color-mixing apparatus. One of these three dimensions is most naturally taken to be the (achromatic) dimension of *lightness*—as represented, in purest form, by the shades of gray ranging from black to white. The two remaining (chromatic) dimensions can be taken to be a circular dimension of *hue,* which, in cycling through the spectrally pure colors of red, orange, yellow, green, blue, and violet, forms Newton's color circle; and a radial dimension of *saturation,* which varies between each of these spectrally pure hues and a central, neutral gray of the same lightness. (Again, see Figure 13.1a.)

Alternatively, and in agreement with the opponent-process theory of color vision proposed by Ewald Hering (1878/1964) and given a modern development by Hurvich and Jameson (1957), the two chromatic dimensions can be taken to be a rectilinear red-versus-green dimension and an orthogonal yellow-versus-blue (or yellow-versus-violet) dimension—as illustrated in Figure 13.1b. Whether we thus describe the underlying three-dimensional color space using polar chromatic coordinates of hue and saturation (Figure 13.1a) or using rectangular chromatic coordinates of redness versus greenness and of yellowness versus blueness (Figure 13.1b), all colors can be obtained by an appropriate combination of values on the three chosen dimensions.

Inadequacy of Some Proposed Explanations for Trichromacy

Given that the human visual system normally provides just three dimensions for the representation of colors, a question immediately presents itself: Why exactly three dimensions, rather than, say, two or four? Three answers that might first suggest themselves all prove, on closer consideration, to be inadequate.

Is Trichromacy Explained by the Physical Properites of Surfaces?

Inherent physical properties of the surfaces in the external world do indeed determine which colors we perceive those surfaces to have—out of a three-dimensional set of alternative colors that we are capable of representing. Those physical properties of surfaces evidently do not, however, determine the dimensionality of our set of alternative color representations. What the inherent physical properties of a surface really determine is the spectral reflectance distribution of the surface; and the spectral reflectance distribution, being defined over a continuum of wavelengths, can require an unlimited number of quantities in order for us to specify the relative amount of light that would be reflected back for each wavelength between 400 and 700 nm. True, the spectral reflectance functions of wavelength for naturally occurring surfaces are generally smooth functions, and such smoothness implies the possibility of some dimensional reduction. Evidently, though, the smoothnesses are only sufficient to permit a reduction to somewhere between five and seven dimensions (Maloney, 1986). The further compression to the three dimensions of color that we experience cannot be attributed to a property of the surfaces of objects, therefore, but must be imposed by our visual system. The empirically verifiable consequence is that there are surfaces (called *metameric* surfaces) that have different spectral reflectance distributions according to physical measurements and yet to our eyes are perceptually indistinguishable in color.

Is Trichromacy Explained by Our Possession of Just Three Types of Cone?

As is well known, human color vision is mediated by three types of retinal cones, whose photochemical pigments have peak sensitivities tuned, respectively, to longer, middle, and shorter wavelengths in the visible range. This fact can certainly be taken to explain *how* the dimensional compression is imposed by the human visual system. But it only transforms the question of *why* there is such a dimensional compression from the question of why we experience just three dimensions of color into the still unanswered question of why our retinas possess just three classes of color sensitive units.

Is Trichromacy Explained by a Trade-off Between Chromatic and Spatial Resolution?

Possibly the majority of contemporary vision scientists regards the three-dimensionality of human color representation as a more pragmatic, somewhat arbitrary compromise between competing pressures toward the one-dimensional simplicity of achromatic (colorless) vision and the high-dimensional complexity of the truly full-color vision that would wholly capture the intrinsic spectral reflectance distribution of each and every external surface. Among our distant hunter-gatherer ancestors, those having only two types of cones and, hence, only two-dimensions of color vision might have been at a slight but (in the long run) significant disadvantage in identifying foods, mates, predators, and the like. At the same time, any ancestors that, through spontaneous mutation, might have had cones of more than three types and, hence, four or more dimensions of color vision might have lost in precision of form discrimination more than they gained in refinement of object identification through color. For, in order to accommodate an additional class of color-sensitive retinal receptors, the receptors of some class or classes would necessarily have to be less densely distributed across the retina. Indeed, there may be some validity to this third answer. Still, it is unsatisfyingly nonspecific and post hoc. It makes plausible that the number of chromatically distinct receptor classes has some optimum value, but it gives no reason why this optimum number is specifically three. Essentially the same argument could have been offered if our color vision were instead, say, two-dimensional or four- or five-dimensional.

An Alternative Basis for Trichromacy in the Degrees of Freedom of Terrestrial Illumination

In order to explain the specifically three-dimensional character of our color representation, I have been advancing a fourth, quite different possible answer (Shepard, 1990, 1991; see also, Shepard, 1987a). Given that our visual systems do not capture the full reflectance characteristics of a surface anyway, perhaps we should shift our focus away from the question of how we perceive the true color of a surface and focus, instead, on how the color that we do perceive is nevertheless the *same* color each time we view the same surface. It is after all this constancy of color that is most essential for identifying objects and, hence, for behaving appropriately with respect to them. In particular, the possibility I have been putting forward is that our visual systems analyze inputs into three color dimensions because three is the number of degrees of freedom of terrestrial illumination—degrees of freedom that must be compensated for in order to achieve constancy of perceived surface colors.

I was led to this possibility by what I took to be an implication of the general linear model for color vision proposed by Maloney and Wandell (1986). This implication concerns a hypothetical animal whose survival and reproduction depends only on its perception of the shapes and relative lightnesses of objects and not at all on their chromatic colors. It appeared to me that such an animal, although requiring only a shades-of-gray representation of its world, could nevertheless achieve constancy of its (achromatic) representation only if its visual system first analyzed the optical input into three chromatic channels. (I am assuming, again, that those channels—like actual photoreceptors—are sufficiently broad-band to make efficient use of available light.) Only in this way could the animal's estimates of the achromatic lightnesses of surrounding surfaces be stabilized against the three degrees of freedom of chromatic composition of natural illumination. (The same would be true, incidentally, for a camera, television system, or robot that was to generate a lightness-constant shades-of-gray, or "black-and-white," image.)

Maloney and Wandell (1986) themselves did not specifically address the question of the minimum number of dimensions needed to achieve color constancy. Rather, they focused on the somewhat different question of the number of dimensions needed to determine, for any surface, the full spectral reflectance function of that surface. As I noted, Maloney and Wandell concluded that, for such a determination, the number of chromatic channels N must exceed by one the number of degrees of freedom of the ensemble of reflectance functions, a number that may itself lie between five and seven (Maloney, 1986).

Suppose, however, that the principal criterion for success of the visual system's chromatic analysis is not that it represent the full complexity of the spectral reflectance function for each surface but that it ensure that the (possibly reduced) representation of each such function is constant under natural variations of illumination. We do not need to make a commitment, here, as to the particular computational method that the visual system uses to estimate the characteristics of the prevailing illumination. It could be an improved version of Land's retinex method, Maloney and Wandell's general linear method, or a method that uses (in addition) more direct information about the characteristics of the illumination (available, say, from a view of the sun, sky, shadows, or specular reflections). For any such method, the general linear model indicates that correction for the momentary characteristics of the illumination that will achieve constancy in the representation of surface colors requires that the number of chromatic channels N equal the number of degrees of freedom of natural illumination—that is, essentially three.

I am not claiming that the chromatic colors of objects themselves are of no biological significance to us, or that we experience color only as a by-product of a mechanism that has evolved to achieve invariance of lightness under changes of illumination. Perceptual constancy is important, but we undoubtedly benefit from having a perceptual representation of the chromatic colors themselves. Laboratory studies have found chromatic color to be a more effective cue for guiding visual search than either lightness or shape (see the review by Christ, 1975). And in a natural setting, a purely shades-of-gray representation of the world, even if lightness-constant, would not enable us to discriminate, say, red from green berries or even to spot ripe berries, with sufficient ease and speed, from a background of green leaves. Undoubtedly, then, a perceptual representation of chromatic surface color is itself favored by natural selection—as is suggested by the important roles it has been found to play in the behaviors of many animals (e.g., Fernald, 1984; Hardin, 1990; Jacobs, 1981; Lythgoe, 1979).

For most human purposes, however, the gain in going to the six or more chromatic channels that (according to Maloney, 1986) might be required to discriminate between all naturally occurring surface reflectance functions would probably not offset the costs of reduced spatial resolution and increased computational burden. It is, then, on the assumption that some relatively small number of color dimensions suffices for the discrimination and recognition of biologically significant objects that I propose that the precise number of dimensions of our color representation may have been determined, instead, by the number of degrees of freedom of terrestrial illumination that must be compensated for in order to obtain perceptual constancy of the colors that we do experience.

The Physical Basis of the Three Degrees of Freedom of Natural Illumination

The solar source of significant terrestrial illumination has probably been essentially invariant in the spectral composition of its output throughout recent evolutionary history. The energy distribution of the portion of that sunlight illuminating any particular terrestrial scene has nevertheless varied greatly from circumstance to circumstance (e.g., see Condit & Grum, 1964; Judd et al., 1964; McFarland & Munz, 1975a, 1975b; Sastri & Das, 1968). Yet, this variation has evidently been constrained by terrestrial conditions to essentially three independent dimensions (see Judd et al., 1964). Indeed, these three environmental degrees of freedom appear to bear a close correspondence to the three dimensions of color opponency that Hering (1878/1964) and Hurvich and Jameson (1957) proposed for the human visual system on the basis of entirely different (psychophysical rather than ecological) considerations.

The Light-Dark Variation

There is, first, the dimension of variation in overall intensity of illumination between midday and deep shade or moonlight. This variation can occur, moreover, without much shift in chromatic composition. Under natural conditions, the brightest extreme of this variation is generally provided by the full complement of light from an overhead sun on a clear day—including both the yellow-biased, middle- to long-wavelength portion that directly penetrates to a scene and the blue-biased, short-wavelength portion that is indirectly scattered to the scene by the surrounding sky. Much less bright illumination that nevertheless has a similar spectral composition can arise through the chromatically nonselective filtering that may occur when, for example, the same sort of light (from sun and sky) reaches a scene only after being scattered to it from chromatically neutral surfaces such as white clouds, grey cliffs, or the moon. Indeed, moonlight, though vastly reduced below daylight intensities, has essentially the same spectral composition, because the lunar surface reflects all solar wavelengths within the visible range about equally (Lythgoe, 1979).

The Yellow-Blue Variation

This second, chromatic dimension of variation arises primarily as a result of Raleigh scattering (see Born & Wolf, 1970; Lythgoe, 1979). The shortest (blue and violet) wavelengths of light are most scattered by the smallest particles in the atmosphere—particularly the molecules of the air itself. (As the particles in the air become larger, the distribution of scattered wavelengths becomes more uniform—so that larger water droplets, for example, give rise to the achromatic, white or gray appearance of haze, fog, or clouds.) A blue extreme in natural lighting therefore occurs when a relatively localized object (such as a tree or cloud) blocks direct sunlight from striking the scene, while permitting unobstructed illumination of that scene by the light scattered to it from an otherwise clear sky—particularly from those portions of the sky that are separated from the sun by a large celestial angle (see Lythgoe, 1979; McFarland & Munz, 1975a). The contrasting yellow extreme occurs under the complementary condition in which a portion of a scene is illuminated only by direct sunlight—as by a beam of sunlight admitted by a small opening in a cave, leafy canopy, or handmade shelter—with all skylight cut off. Such purely direct solar light does not of course consist solely of wavelengths in the yellow region of the spectrum. Rather, I call it yellow because, after removal of the shortest (blue and violet) wavelengths, the center of the remaining band of visible wavelengths falls in the yellow region of the spectrum and because these remaining wavelengths, when combined, can give rise (like the disk of the overhead sun itself) to a correspondingly yellow appearance.

The Red-Green Variation

This third dimension of variation depends both on the elevation of the sun and on the atmospheric burden of water vapor. The longest (red) wavelengths are least scattered by air molecules and other small atmospherically suspended particles (such as dust). But those wavelengths are also most absorbed by any water that they encounter. In the relative absence of water vapor, the sunlight that directly strikes a scene will have retained a relatively greater proportion of its longest-wavelength, red component as the sun approaches the horizon, and, hence, its light must penetrate a longer and (at the lower altitude) denser column of air and suspended particles before striking the scene. When the atmosphere carries a high burden of water vapor, on the other hand, the penetrating light will contain a reduced component of long-wavelength red light. (There is, incidentally, an asymmetry between the lighting conditions at sunrise and sunset because even when the sun is in the same proximity to the horizon, the preceding temperature and hence burden of water vapor will generally be different in the two cases.) For both sources of the red variation (elevation of the sun and presence of water vapor), the argument for putting green in opposition to red is essentially the same as the argument for putting yellow in opposition to blue. After removal of the longest-wavelength, red end of the visible spectrum, the center of the remaining band of visible wavelengths falls in the green portion of the spectrum.

From a purely mathematical standpoint, of course, any (nondegenerate) coordinate system is equivalent to any other in the sense that either can be obtained from the other by a suitable (nonsingular) transformation. Thus, as I have already noted, the points of three-dimensional color space can be represented by either the polar or the rectangular coordinate systems shown in Figure 13.1a and 13.1b. Similarly, as I also noted, a linear transformation could convert the three basis functions plotted in

Figure 13.2 into three differently shaped, but functionally equivalent basis functions. With respect to simplicity and efficiency of computation, however, a visual system that represents color in terms of the particular light-dark, yellow-blue, and red-green dimensions that correspond most directly to the underlying physical dimensions of variation of natural illumination in the terrestrial environment might most effectively compensate for these variations and, thus, attain color constancy.

Recapitulation and Consideration of Some Counterexamples and Methodological Issues

Recapitulation of the Argument Concerning the Source of Trichromacy

The visual system starts with a retinal input in which, at any one moment, each receptor unit (cone) receives some distribution of intensities of wavelengths between roughly 400 and 700 nm. For the purposes of identifying objects and responding adaptively to them, the visual system must analyze this complex input into two components—one corresponding to the biologically significant, invariant properties of objects (regarded as the "signal") and one corresponding to the biologically less significant momentary circumstances of viewing and lighting (regarded as the "noise"). With regard to the perception of the colors of objects, this is just the color constancy problem of analyzing the distribution of spectral energies impinging at each point of the retina into a component that captures some invariant characteristic of the surface of an object and a complementary component attributable to the momentary conditions of illumination.

I have suggested that the visual system has solved the problem of performing this analysis and hence of attaining color constancy by first analyzing the visual input into the minimum number of chromatic channels needed to carry out the required analysis, namely, three. If this suggestion is correct, the human visual system provides for three dimensions of representation of colors because there are, in fact, three corresponding degrees of freedom in the world. But these three degrees of freedom in the world are not the degrees of freedom of the intrinsic colors of surfaces, which evidently are greater than three (Maloney, 1986). Instead, the critical degrees of freedom in the world may be those of natural illumination in the terrestrial environment.

The overall (400 to 700 nm) range of spectral sensitivity of the human eye has long been regarded as an evolutionary accommodation to the range of solar wavelengths that reach us through the earth's atmosphere (and through the aqueous medium of our eyes—and, originally, of the sea from which our distant ancestors emerged) (e.g., see Jacobs, 1981; Lythgoe, 1979). Possibly, the three-dimensionality of human color vision may similarly represent an evolutionary accommodation to the essentially three degrees of freedom of terrestrial transformation of the solar wavelengths passed by the earth's atmosphere.

Based on considerations of the physical causes of these natural variations of terrestrial lighting (cf. Condit & Grum, 1964; Judd et al., 1964; McFarland & Munz, 1975a, 1975b; Sastri & Das, 1968), I have further conjectured that these three degrees of freedom may be essentially characterized as a light-dark variation (between unobstructed midday illumination versus illumination of the same composition but greatly reduced intensity that reaches the scene only by scattering from clouds, cliffs, or the moon), a yellow-blue variation (between illumination primarily reaching an object directly from an overhead sun versus indirectly by Raleigh scattering from clear sky), and a red-green variation (depending on the proximity of the sun to the horizon and the amount of water vapor in the air). If so, a selective advantage may have been conferred on genes for the development of a neural mechanism that combines and transforms the outputs of the three classes of retinal receptors into the three specific opponent-process dimensions proposed, on quite different grounds, by Hering (1878/1964) and by Hurvich and Jameson (1957).

Consideration of Some Apparent Counterexamples

Color constancy is neither perfect nor unconditional, however (e.g., see Helson, 1938; Judd, 1940; Worthy, 1985). Our own visual mechanisms have been shaped by the particular selective pressures that have operated under the natural conditions generally prevailing on planet Earth during mammalian evolution. Not surprisingly, therefore, our color constancy can break down under artificial lighting. On an evolutionary time scale, such lighting has begun to fall on our indoor or nocturnal surroundings for too short a time for selection pressures on our visual mechanisms to compensate for the new degrees of freedom introduced by such lighting. At night, we may thus fail to recognize our own car in a parking lot illuminated only by sodium or mercury vapor lamps.

To claim that the selection pressure that prevailed until very recently in the natural environment has been toward three dimensions of color representation is not, of course, to claim that this pressure has been great enough to override all other selection pressures and, hence, to ensure trichromacy in all highly visual terrestrial species. Although the once widespread belief that color vision is absent in many mammals, even including cats or dogs, is undoubtedly incorrect (Jacobs, 1981), a number of species with otherwise well-developed visual systems have been reported to lack three-dimensional color representation. Thus, while old-world monkeys evidently tend, like humans, to be trichromatic, evidence concerning new-world monkeys has pointed to dichromacy and to trichromacy in different species.

Even in humans, approximations to dichromacy occur in about 8% of the population (primarily in males, because nearly all forms of congenital color deficiencies are determined by sex-linked genes—Jacobs, 1981; Nathans, Thomas, & Hogness, 1986). Most typically, human color deficiency takes the form of some degree of collapse of color space along the red-green dimension (see Figure 13.1b). In extreme cases of this particular type of collapse *(protanopia),* human trichromacy may be reduced to pure dichromacy. Total color blindness, that is, *monochromacy,* also occurs in otherwise sighted humans—either because the color-selective retinal cones are absent (leaving only the achromatic retinal receptors, called rods) or because the neural circuitry necessary for the proper analysis of the outputs of the cones is missing or defective (see Alpern, 1974; Jacobs, 1981). Pure monochromacy of this sort is extremely rare in humans, however, as might be expected if color vision and/or lightness constancy significantly contributed to the adaptation of our ancestors.

Because a relatively large portion of the variance in the spectral distributions of natural light can be accounted for by as few as two dimensions (see, e.g., Dixon, 1978; Judd et al., 1964), a degree of color constancy that is acceptable under most natural conditions may be attainable with just two classes of cones and, hence, with just two chromatic channels of visual input. Moreover, the addition of each new class of retinal receptors entails both costs of reduced spatial resolution for each class and costs of additional neural processing structures. Nevertheless, in the long run, genes for three-dimensional color vision—genes that are already being identified and localized on human chromosomes (Nathans, Thomas, & Hogness, 1986)—may provide a sufficient contribution to color constancy so that such genes eventually tend to prevail in the most visually developed evolutionary lines. Even as remote a species as the honey bee, the insect whose color vision has been most thoroughly studied (Lythgoe, 1979), has been reported to be trichromatic (Daumer, 1956) with, in fact, color vision very much like our own (LeGrand, 1964), except that its visual sensitivity is somewhat shifted, as a whole, toward the shorter wavelengths (von Helverson, 1972).

Methodological Issues Concerning the Determination of Dimensionality

From the standpoint taken here, the dimensionality of an animal's perceptual representation of colors is perhaps the single most fundamental characteristic of that animal's color vision (cf. Jacobs, 1981, pp. 21–22). Yet, this dimensionality remains undetermined for most highly visual species. The dimensionality of color representation is in fact quite difficult to determine in nonhuman species, and it becomes more difficult in more remote species. (In a closely related primate species we might make an inference as to the dimensionality of color vision from the anatomical presence or absence of each of the three types of cones that mediate trichromacy in our own case.) As I have mentioned, the number of unidimensional variables whose adjustment is sufficient to achieve a visual match with any given color is equivalent to the dimensionality of color space for the species doing the matching. But, for a very different species, how do we know which of the potentially countless dimensions along which spectral distributions can differ are to be varied? And, although we might train an animal to make a particular response when and only when two displayed colors are indiscriminable for that animal, how do we train the animal to adjust several unidimensional controls, simultaneously, to achieve such a visual match?

In principle, the dimensionality of a space can be determined from the relations among a fixed, finite set of points (or stimuli), without requiring continuous adjustment or matching. The difficulty with this approach is that the dimensionality of the space is not a property of single points or, indeed, of pairs or of triplets of points. Rather, it is a property determined by the distances between all points (or, in the case under consideration, the dissimilarities between all colors) in sets containing a number of points (or colors) that is one greater than the number of dimensions of the space (Blumenthal, 1953). Multidimensional scaling—particularly multidimensional scaling of the so-called nonmetric variety (Kruskal, 1964; Shepard, 1962, 1980)—can permit a determination of the dimensionality of a finite set of stimuli. Such a method requires, however, obtaining estimates of the animal's perceived similarities or dissimilarities between most of the stimuli in the set. Humans readily give numerical ratings of similarity, but in the case of other animals such estimates may have to be based on the extent to which a response learned to each stimulus generalizes to each of the others or on latencies or frequencies of errors in matching-to-sample responses (e.g., see Blough, 1982; Shepard, 1965, 1986). Unfortunately, the training and data collection would require a major research effort for each species and each set of colored surfaces investigated.

Rather than attempting to determine the dimensionality of color representation in different species by means of multidimensional scaling, researchers have mostly pursued their comparative studies of the color capabilities of different species (a) anatomically or physiologically, by trying to determine the number of distinct types of receptor units (such as retinal cones having photosensitive pigments or oil-droplet filters with different wavelength characteristics), or (b) psychophysically, by measuring discriminability between neighboring spectrally pure colors at different locations along the continuum of wavelength. Neither of these methods provides, however, a reliable indication of the dimensionality of the animal's perceptual representation of colors.

From anatomical examination, one may never be sure that one has found every chromatically distinct type of receptor unit. Even if one could, there is no guarantee that the number of dimensions of color representation is as large as the number of types found. The outputs of two or more types of photoreceptors with different spectral sensitivities might be neurally combined into one chromatic channel somewhere up the line. (Indeed, humans, normally have four identified types of retinal photoreceptors—namely, cones of three types and rods of one type, each type with its peak sensitivity at a different wavelength. Yet, humans normally have only three dimensions of color representation.)

The psychophysically determined wavelength discrimination function is even less informative about the dimensionality of an animal's color representation. For example, an animal could discriminate an arbitrarily large number of wavelengths and still represent all those spectrally pure colors on a single dimension of hue, just as an individual could discriminate an arbitrarily large number of intensity levels and still represent those shades of gray on a single dimension of lightness. The question of dimensionality depends not on the number of discriminably different wavelengths but on the discriminabilities of all possible mixtures of such wavelengths. But the number of pairs of mixtures that might be tested increases radically with the number of discriminable wavelengths to be mixed.

A single example may suffice to illustrate the problem. The color capabilities of pigeons have been extensively investigated psychophysically as well as anatomically. Their wavelength discrimination function has been measured (Hamilton & Coleman, 1933; Wright, 1972), and evidence has been found for at least six chromatically distinct types of retinal cones—having different wavelength-selective combinations of photopigments and colored oil-droplet filters (Bowmaker, 1977; Bowmaker & Knowles, 1977). Nevertheless, to my knowledge, the question remains open as to whether the pigeon is trichromatic, as we are, or whether it has as many as four, five, or six dimensions of color representation. Conceivably, in the pigeon there has been sufficient selection pressure not only toward the three chromatic channels needed for the achievement of color constancy in the natural environment, but also toward the additional chromatic channels that, according to Maloney and Wandell's (1986) general linear model together with Maloney's (1986) estimate of the number of degrees of freedom of the spectral reflectance distributions of natural surfaces, might be required to capture fully the intrinsic reflectance characteristics of natural objects or foods.

THE CIRCULAR STRUCTURE OF SPECTRALLY PURE COLORS

Another one of the facts that I included in my initial, illustrative list of structural constraints on human perception and cognition is the fact that the physically rectilinear continuum of wavelength is transformed by the human visual system into the psychologically circular continuum of perceived hues—that is, into Newton's (1704) color circle, schematically portrayed as the equator of color space in Figure 13.1a. Such a circle can be recovered with considerable precision by applying methods of multidimensional scaling to human judgments of the similarities among spectral hues (Shepard, 1962; Shepard & Cooper, 1992). The circularity is implied, as I noted, by the observation that red and violet, although maximally separated in physical wavelength, appear more similar to each other than either does to green, which is of an intermediate wavelength.

I conjecture that this circularity of hue may have arisen as a consequence of the transformation by which the human visual system carries the responses of three classes of retinal photoreceptors (the cones most sensitive to long, medium, and short wavelengths) into the three opponent processes (the light-dark, yellow-blue, and red-green processes). If so, not only the three-dimensionality of color space but also the specifically circular character of the hue dimension, rather than being an arbitrary design feature of the human visual system, may be traceable to an enduring regularity in the terrestrial world in which we have evolved.

The Circularity of Hue as an Accommodation to the Degrees of Freedom of Terrestrial Illumination

In rough outline, the argument runs as follows: The extremes of the range of solar wavelengths admitted through the terrestrial "window" on the solar spectrum are, naturally, the most affected by any variations in that "window." Thus, the longest wavelengths (the red components) are both least scattered by atmospherically suspended particles and most absorbed by water vapor, and the shortest wavelengths (the blue and violet components) are most scattered by the smallest atmospheric particles—particularly by the molecules of the air itself. Now, if the variable component of longest visible wavelengths (the reds) is put in opposition to the rest of the visible wavelengths, the central tendency of those opposing wavelengths will be what we call green—not the visible wavelengths that are physically most remote from the reds (namely, the short wavelength violets). Similarly, if the independently variable component of shortest visible wavelengths (the blues and violets) are put in opposition to the rest of the visible wavelengths, the central tendency of those opposing wavelengths will be what we call yellow—not the visible wavelengths that are physically most remote from the violets and blues (namely, the long wavelength reds).

Accordingly, a transformation by the visual system from the outputs of three classes of cones to an opponent process representation has the effect of bending the physically rectilinear continuum of wavelength into a closed cycle of spectral hues. Whereas in the original physical continuum, the extreme opposites were red and violet, in the resulting cycle of hues, the opposites (schematically thought of as the diagonally opposite corners of a square) are red and green (across one diagonal) and yellow and blue/violet (across the other diagonal). The originally most remote hues of red and violet, being now separated by only one edge of the (schematic) square, become closer together than the now diagonally separated red and green or the now diagonally separated yellow and blue/violet. (The red, yellow, green, and blue "corners" are in fact quite evident in the [squarish] version of the color circle that emerged when Carroll and I applied multidimensional scaling to color naming data collected by Boynton and Gordon [1965] for 23 spectral hues [see Shepard & Carroll, 1966, Figure 6, p. 575].)

Evidence Suggestive of an Innate Structure for the Representation of Colors at Higher Levels of the Brain

Color vision requires, in any case, not only wavelength-selective receptors (the retinal cones) but also some processing machinery for estimating from the variable outputs of those receptors the invariant colors of distal objects. Presumably, moreover, the genes specifying the structure of such neuronal circuitry will generally lead to the development of that circuitry in each individual whether or not that circuitry is destined to receive normal signals from that particular individual's retinal receptors. For example, an individual who is missing the gene for one of the classes of wavelength-selective cones may, through an inability to discriminate between certain presented colors (such as red and green), give evidence of a collapsed, two-dimensional color space. But this does not preclude that individual's possession, at higher levels of the nervous system, of the circuits that have been evolutionarily shaped for representing the full, three-dimensional system of colors.

In an investigation of the representation of colors by normally sighted, color-blind, and totally blind individuals (Shepard & Cooper, 1992), Lynn Cooper and I found evidence that suggests this is the case and thus contradicts the central tenet of the British empiricist philosophers—that everything that each individual knows must have first entered through that individual's own sensory experience. We asked the individuals with the different types of normal and anomalous color vision to judge the similarities among saturated hues under two conditions: (a) when pairs of those hues were actually presented (as colored papers), and (b) when the pairs of hues were merely named (e.g., "red" compared with "orange"). We applied multidimensional scaling to the resulting similarity data for each type of individual and for each of the two conditions of presentation. Most striking were the results for the red-green color-blind individuals (*protans* and *deutans*). As expected, when the colors were actually presented to these individuals, multidimensional scaling yielded a degenerate version of Newton's color circle with the red and green sides of the circle collapsed together. Significantly, however, when only the names of the colors were presented, multidimensional scaling yielded the standard, nondegenerate color circle obtained from color-normal individuals (cf. Shepard, 1962, p. 236; 1975, p. 97).

One particularly articulate protan insisted that although he could not distinguish the (highly saturated) red and green we showed him, neither of these papers came anywhere near matching up to the vivid red and green he could imagine! In a sense, then, the internal representation of colors appears to be three-dimensional even for those who, owing to a purely sensory deficit, can only discriminate externally presented colors along two dimensions (most commonly, the dimensions of light versus dark and yellow versus blue indicated in Figure 13.1b).

Incidentally, it was in the domain of colors that the preeminent British empiricist, David Hume, acknowledged what he considered to be the one possible exception to the empiricists' central maxim. Hume, on supposing "a person to have enjoyed his sight for thirty years, and to have become perfectly well acquainted with colours of all kinds, excepting one particular shade of blue," confessed to favoring an affirmative answer to the question of "whether 'tis possible for him, from his own imagination, to supply this deficiency, and raise up to himself the idea of that particular shade, tho' it had never been conveyed to him by his senses?" Despite this admission, Hume concluded, somewhat lamely, that "the instance is so particular and singular, that 'tis scarce worth our observing, and does not merit that for it alone we should alter our general maxim" (Hume, 1739/1896, p. 6).

THE ORGANIZATION OF COLORS INTO CATEGORIES AND PROTOTYPES

Phenomena of color vision run counter not only to the central tenet of the British empiricists but also to the views of the more recent American linguistic relativists. According to the latter, as represented particularly by Sapir (1916) and Whorf (1956), each language lexically encodes experience in a way that is unique to the culture in which that language evolved. Color offers a particularly suitable domain for testing this idea because each color, as experienced by human observers, is a relatively "unitary" or "unanalyzable" percept (Shepard, 1964, 1991; Shepard & Chang, 1963), corresponding to a single point in the color space schematically portrayed in Figure 13.1. If linguistic relativity were valid, the way continuous color space is divided into regions for the purposes of assigning discrete names to colors would be expected to differ in more or less arbitrary ways from one language to another. Empirical studies, however, have uncovered a striking degree of cross-cultural uniformity.

The Cross-Cultural Findings of Berlin and Kay

Together with their co-workers, Berlin and Kay (1969) presented native speakers of 20 diverse languages with an array of 329 Munsell color chips, including 320 maximum saturation colors differing in equally spaced steps of hue and lightness, which had originally been used in a comparison of English and Zuni color terminology by Lenneberg and Roberts (1956), and 9 additional zero-saturation shades of gray. For each basic color term, *x*, in an informant's native language, the informant was asked to use a black grease pencil to encircle, on an acetate sheet overlaying the array of color chips, (a) the set of colors that the informant "would under any conditions call *x*" and, then, (b) the subset of those colors that the informant regarded as "the best, most typical examples of *x*" (Berlin & Kay, 1969, p. 7).

Berlin and Kay found that the color terms in different languages did not correspond to arbitrarily overlapping regions in color space. Instead, the terms were essentially consistent with a universal underlying hierarchy of nonoverlapping regions in color space for each of the 20 languages directly investigated (and these results appeared to be consistent with the reports, by others, of the use of color terms in some 78 other languages). The languages differed primarily in the number of basic color terms they included. They differed very little in the locations of the regions corresponding to the basic color terms that they did include. In particular, the languages generally conformed with a partial order of color categories (that is, regions of color space) that—in terms of the English names that we assign to these categories—is as follows:

$$\begin{Bmatrix}\text{white}\\ \text{black}\end{Bmatrix} < \{\text{red}\} < \begin{Bmatrix}\text{green}\\ \text{yellow}\end{Bmatrix} < \{\text{blue}\} < \{\text{brown}\} < \begin{Bmatrix}\text{purple}\\ \text{pink}\\ \text{orange}\\ \text{gray}\end{Bmatrix}$$

"where, for distinct color categories (*a*, *b*), the expression $a < b$ signifies that *a* is present in every language in which *b* is present and also in some language in which *b* is not present" (Berlin & Kay, 1969, p. 4).

The regions in color space corresponding to these apparently universal color categories are (with the exception of the region for the completely unsaturated grays) conveniently displayed on the hue-by-lightness rectangle, which (as indicated in Figure 13.3) can be thought of as a Mercator projection of the maximum-saturation surface of the sphere of colors previously illustrated in Figure 13.1. (Because the achromatic color gray corresponds to the center of the sphere, it is not representable on the projection of the surface of the sphere.) The placement of the English names for the successive hues, "Red," "Orange," "Yellow," etc., is only schematic in Figure 13.3; hue and lightness turn out to be universally correlated in the locations of prototypical colors in such a way that yellow, in addition to falling between red and green in hue, is much lighter than these (and the other) basic hues.

Figure 13.4 is my adaptation of the figure in which Berlin and Kay summarized the results of their own study of color naming by native speakers of 20 different languages. The consistently found locations of the basic color categories are displayed within the two-dimensional hue-by-lightness Mercator projection of the maximum-saturation surface of color space. The encircled regions approximate the areas within which the colors chosen as "the best, most typical examples" of the corresponding basic color terms consistently fell according to informants from the various cultures. These focal color categories are labeled, for our convenience, by the basic terms that we use for these colors in English.

Surrounding each of these encircled focal regions, a larger region to which informants indicated the same color term might be extended under some condition is roughly indicated by the penumbra of corresponding initial letters, "G" for "Green," "Br" for "Brown," and so on. Again, however, some of the languages did not have basic color terms for some of the lower categories in the hierarchy, such as the categories here labeled "Pink," "Purple," or "Orange." In these cases, the penumbra surrounding the neighboring focal color regions that were represented in the language

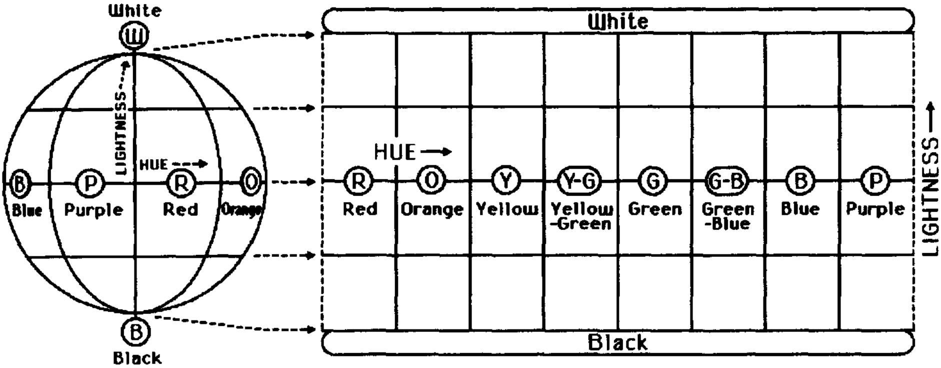

Figure 13.3 Schematic diagram of how the surface of the three-dimensional color space shown in Figure 13.1 can be unwrapped (by Mercator projection) into a rectangular map in which each point represents the most saturated color of a corresponding hue and lightness.

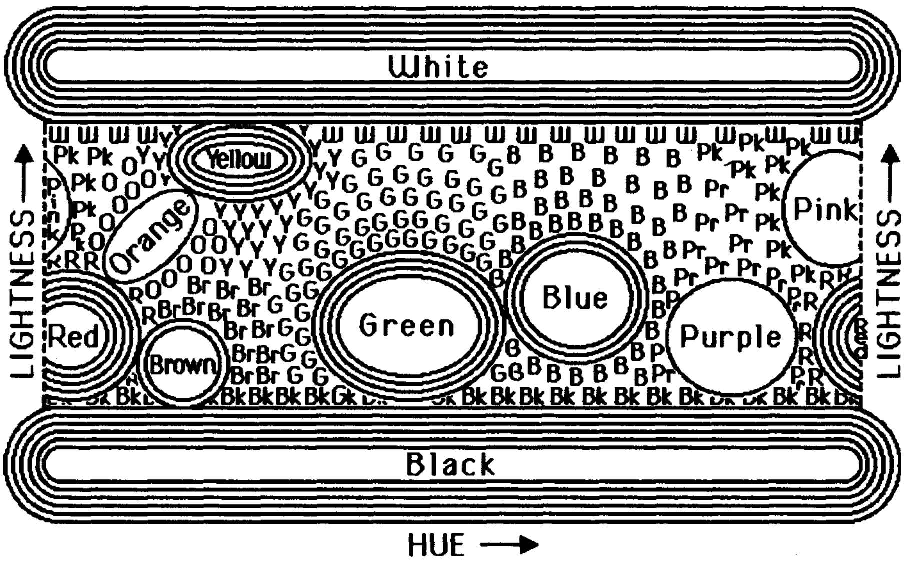

Figure 13.4 Schematic representation of regions, within the rectangular map of saturated colors (as diagramed in Figure 13.3), for which color names are commonly used in different cultures. The name printed within each region is the color word most often used by English-speaking informants. The number of lines drawn around each region indicates the cross-cultural prevalence of assigning a distinct color term specifically to that region. The penumbra of letters ("Gr" for "Green," "Br" for "Brown," etc.) indicates a larger region that the color term might be extended to under some conditions, according to informants. (Adapted from Figure 3 on page 9 of Berlin & Kay, 1969; copyright, University of California Press, 1969.)

might extend through the region lacking its own basic color term. Thus, if the language contained no basic term specifically for the colors in the category here labeled "Purple," the terms for the neighboring regions here labeled "Blue" or "Red" might be extended into the region to which we apply the word "Purple." Also, of course, the colors falling in the penumbra around a given focal color region might be distinguished by the basic color term together with a qualifier. In English, for example, "light green" or "pale green" might be used for colors falling above the focal region for green, and "blue-green" might be used for colors falling between the focal regions for blue and green. And some languages have single terms for still lower levels of the hierarchy. Thus, in English we might use the word "lavender" for light purple, "chartreuse" for yellow-green, and "navy" for dark blue (or blue-black).

I have indicated the hierarchical structure that Berlin and Kay found for the focal colors by encircling each corresponding subregion of color space by an appropriate number of lines. Thus I have drawn six lines around the universally named focal color categories corresponding to our "White" and "Black," five lines around the next most prevalently named category, corresponding to our "Red," and so on for successively lower levels in the hierarchy—"Green" and "Yellow" (four lines each), "Blue" (three lines), "Brown" (two lines), and "Pink," "Purple," and "Orange" (a single encircling line for each).

The rectangular Mercator projection of a globe is equivalent to a cylinder in that the right and left edges of the rectangle correspond to the same meridian on the sphere and, hence, to the same series of colors (here, the reds varying in lightness from darkest red to lightest pink). Thus the focal regions labeled "Red" and "Pink" in Figure 13.4 overlap both the left and right ends of the rectangle as displayed in that figure. (As I have already remarked, the surface color purple is not fully represented in the pure spectral colors of monochromatic light such as arise from a prism or in a rainbow. Surfaces that we call purple are surfaces that reflect a mixture of the longest and shortest of the visible wavelengths, that is, a mixture of red and violet.)

Additional, Corroborating Results and Implications

The locations in color space of the universal focal color regions can usefully be displayed in another way—namely, as these regions would project onto a flat plane cutting through that three-dimensional space, for example, the horizontal plane pictured as passing through the equator of the sphere in Figure 13.1. Figure 13.5 shows my adaptation of such a plot obtained by Boynton and Olson (1987) on the basis of single-word (monolexemic) color naming of 424 color samples by seven English-speaking observers. Here again, each region within which colors were given a particular color name is filled in with the initial letter of that color (e.g., with "G"s for "Green"). The point within such a region that, on average, was accepted as the best example of that

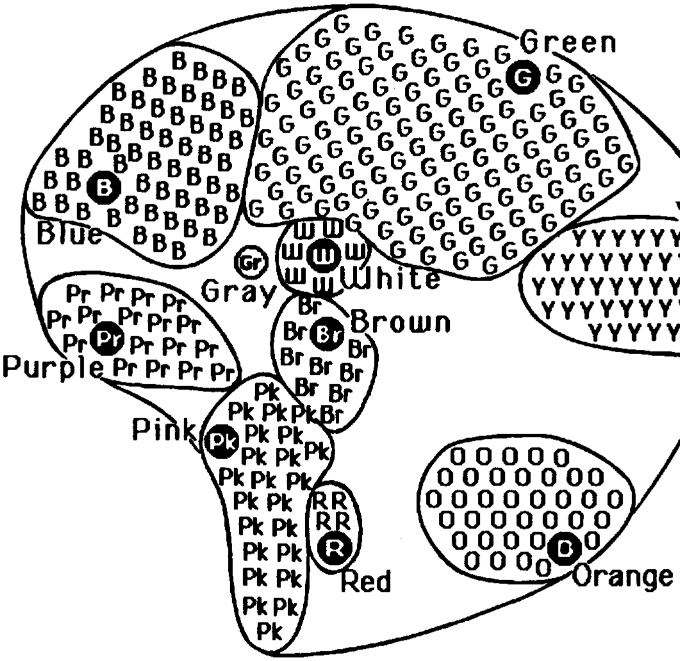

Figure 13.5 Regions of color space for which color names are commonly used, projected (by parallel projection) onto the equatorial disk cutting through the spherical model illustrated in Figure 13.1, according to data reported by Boynton and Olson (1987). (Adapted from Figure 2 on page 99 of Boynton & Olson, 1987; copyright, John Wiley & Sons, Inc., 1987.)

color, considered the focal color for that region, is indicated by the black circle (with a corresponding white letter, e.g., "G").

The dimensions of this two-dimensional projection of color space are not hue and lightness, as in the Mercator projection of Figure 13.4. Instead, the two dimensions here can be considered to be the polar-coordinate dimensions of hue (now represented as a complete circle around the perimeter) and saturation (which is now represented as radial distance out from the unsaturated white and gray near the center to the maximum saturation hues around the perimeter). The focal chromatic colors are not located at the centers of their regions but out toward the maximum saturation perimeter. As noted before, the dimensions of this same projection of color space can alternatively be taken to be the rectangular-coordinate dimensions of red-versus-green (roughly vertical in Figure 13.5) and blue-versus-yellow (roughly horizontal).

The disposition of focal color regions obtained by Boynton and Olson (1987) for this projection, though necessarily different, is quite consistent with the disposition of these regions in the Mercator type of projection presented by Berlin and Kay (1969). The representation shown in Figure 13.5, however, better accommodates the less saturated and achromatic colors (brown, gray, and white) and—in requiring no break in the pink-red region—more explicitly maintains the integrity of the hue circle (corresponding to the equator in the more schematic Figures 13.1 and 13.3). The representation in Figure 13.4, on the other hand, more clearly preserves other aspects of color representation—such as that the yellow band of the spectrum appears lighter (or brighter) than the other (red, green, or blue) bands.

The cross-cultural results such as those reported by Berlin and Kay (1969) and by Boynton and his co-workers (especially, Uchikawa & Boynton, 1987, who compared color naming by American and native Japanese observers) provide little support for the Whorfian hypothesis that language structures how we perceive the world. Instead, these results appear to be more consonant with the idea that the innate biology of our perceptual system structures the way we use language.

Physically, the spectrum of solar light seen in a rainbow or refracted by a prism (as in the original investigations by Newton, 1704) is a continuum of wavelengths. Yet we tend to perceive this continuum as divided into a few relatively discrete bands of hue, such as those we call red, orange, yellow, green, blue, and violet. (White, purple, and all unsaturated colors are obtained only by recombining these pure spectral wavelengths, while black is of course obtained by blocking off all visible wavelengths.)

Eleanor Rosch (formerly Heider) and others, in experimental studies with human observers, have shown, in addition, that the most prototypical (or focal) colors within each region of color space tend to be more rapidly and consistently perceived and remembered than nonfocal colors, which are closer to the boundaries between regions, while discrimination between colors appears to be sharper across the boundaries of these regions than within the same region (Heider, 1971, 1972; Rosch, 1973, 1975; see also Boynton & Olson, 1987, 1990; Mervis & Rosch, 1981; Nagy & Sanchez, 1988; Uchikawa & Boynton, 1987).

Moreover, the tendency toward the perceptual categorization of the hue continuum is not unique to human adults, but has been reported to take essentially the same form in human infants (Bornstein, Kessen, & Weiskopf, 1976) and in other primates (Essock, 1977; Sandell, Gross, & Bornstein, 1979). (In monkeys, incidentally, Zeki [1983] found cortical cells whose responses, like our own color-constant experience of surfaces, were determined by the intrinsic reflectance characteristics of an external surface regardless of the illumination.) There is even evidence that the spectral continuum is also perceptually partitioned by such remote species as pigeons and bees, though apparently into color categories that differ somewhat from those common to humans and monkeys (Kühn, 1927; von Frisch, 1950; Wright & Cumming, 1971). For all of these animals, including humans, visual discrimination between neighboring wavelengths has been reported to be sharpest at the boundaries between the color categories for each species (Graham, Turner, & Hurst, 1973; Jacobs & Gaylord, 1967; Nagy & Sanchez, 1988; Smith, 1971; von Helversen, 1972; Wright, 1972). And, as the evidence obtained by Berlin and Kay (1969) and others has shown in the human case, the boundaries tend to be the same across cultures that have developed on widely separated continents and that have very different languages and sets of color terms. Evidently (as concluded by Uchikawa & Boyton, 1987; and, earlier, by Ratliff, 1976), the way in which humans categorize colors is universally prewired rather than individually acquired.

But we are still left with the question of the source of the particular form of such an innate biology underlying human color categorization. Is this biology merely accidental or has it arisen as an accommodation to some identifiable regularity in the world in which we have evolved? Perhaps we should distinguish two questions: First, why is the continuous space of colors partitioned into discrete categories at all? Second, given that it is partitioned, why is it partitioned in the particular way indicated in Figures 13.4 and 13.5?

Possible Adaptive Functions of a Categorical Organization of Colors

In the case of humans, one advantage of an innate structuring of continuous color space into discrete regions, organized around prototypical or focal colors, has already been implicit in the discussion of the linguistic studies by Berlin and Kay and others. Because a discrete structuring makes possible the consistent assignment of words to colors, it facilitates communication between individuals about the colors of objects that may be of biological significance. One may readily identify a person that one is to meet for the first time on the basis of a description of a color that that person will be wearing. But it may be impossible to identify that person on the basis of a description of his or her face. The continuous space of human faces (in addition to being of higher dimensionality) does not seem to be endowed with a consistent categorical structure like that of the continuous space of colors.

Of course, this linguistic advantage of categorical representation of colors cannot be the explanation for the very similar categorical structure that has been demonstrated for the color spaces of other, nonlinguistic species. Still, for the more general purposes of biological signaling within and between species, the categorical representation of colors may have similar advantages, as has been argued by Hardin (1990). The advantages for both of these purposes—for human language and for other types of signaling—can be seen as examples of the general principle of *shareability* enunciated by Freyd (1983, 1990). When cast in evolutionary terms, that principle says that some cognitive structures or functions may arise not because they capture a biologically significant regularity in the physical world but because they facilitate or make possible the sharing of knowledge between conspecifics. Clearly, an innate predisposition toward a consistent partitioning of a biologically significant continuum into discrete categories will facilitate the sharing of knowledge about the things signified by that continuum, whether through changes in the coloration of bodily markings (as in some fish—Fernald, 1984) or through human language (Berlin & Kay, 1969; Kay & McDaniel, 1978; Lenneberg & Roberts, 1956; Miller & Johnson-Laird, 1976).

A categorical structuring can also facilitate communication within an individual—for example, from one information-processing module to another within the same individual's brain (as Freyd has suggested, personal communication, June 1990), or from one occasion to another, across time (Heider, 1972; Rosch, 1975). Certainly, to remember the color of a particular object after a single exposure may be important if that object was, say, a newly encountered predator from which one barely escaped. A clear example of the advantage of perceptual categorization has been reported in the auditory domain, where individuals differ markedly in their abilities to recognize the absolute pitch of a tone (independent of its relation to some other tone). Individuals with this ability of so-called *absolute pitch* are much more accurate in identifying whether a long-delayed second tone is or is not a repetition of an earlier tone (Bachem, 1954).

Possible Sources of the Particular Categorical Organization of Human Colors

Even if we agree that the organization of color space into categories and prototypes can serve adaptive functions, we are still left with the question of why this space is organized in the particular categorical way that it is, rather than in some other categorical way. Consideration of this question necessarily becomes still more speculative. The organization of color space that (along with its presumably genetically entrenched physiological basis) appears ubiquitous in humans and other primates may eventually be found to stem from any mixture of at least three sources: (a) The organization could be a largely accidental or arbitrary solution (out of countless other, equally satisfactory organizations) to the problem of providing a discrete basis for intraspecific signaling, language, or shareability; (b) the organization could reflect something about the natural groupings of the surface reflectance distributions of objects (into ripe versus unripe edible fruits, predators versus prey, and so on) that have long had particular biological significance for our ancestors and those of other primates (cf. Shepard, 1987b); or (c) in line with my conjecture as to the source of the three-dimensionality of color space itself, this organization could reflect something about the ways in which terrestrial lighting has most typically varied during evolutionary history.

To my knowledge, the systematic survey of the spectral reflectance distributions of a large sample of significant surfaces in the natural environment needed to support the second alternative has yet to be undertaken. In the meantime, I find some support for the last alternative in what already appears to be a nonaccidental correspondence between the most entrenched of the human color categories and the generally accepted opponent process dimensions of human color vision, which (as I have noted) seem to correspond to the natural dimensions of terrestrial lighting.

On one hand, the six focal colors that we call white, black, red, green, yellow, and blue (also termed "landmark colors" by Miller & Johnson-Laird, 1976) are highest in the hierarchy of basic color categories according to Berlin and Kay (1969), as I indicated in Figure 13.4 by encircling the corresponding English terms with three or more lines. On the other hand, these are just the six colors that are usually taken to define the ends of the three light-dark, red-green, and yellow-blue dimensions in opponent process theories. Moreover, I have suggested that just these dimensions may be best suited to compensate for the most common variations of terrestrial illumination. (Even the universally lighter appearance of focal yellow may have an ecological basis—possibly in the yellow central tendency of the direct light from an overhead sun after the shorter wavelength blues and violets have been partially filtered out by atmospheric scattering.)

The secondary focal colors, such as those that we call orange, purple, pink, brown, and gray, may be distinguished (when, in a given culture, they are distinguished) in order to fill in the main gaps in color space between the primary focal colors defined by the underlying opponent processes. Boynton has reviewed evidence that people will describe these secondary focal colors as mixtures of other more primary colors, but will not describe the primary focal colors as mixtures of any other colors (Boynton, 1988, p. 91). Thus, orange, purple, and pink will be described as containing red mixed with yellow, blue, and white, respectively, while a prototypical red itself is never described as containing any discernible contribution of a neighboring color such as orange or purple.

In any case, if categorical structuring of colors serves an adaptive function, there need be no powerful selective advantage of one structuring in order for it to prevail over others. A slight predisposition toward one organization, arising perhaps from a quite different, noncategorical source might bias the selection toward that organization over other, otherwise comparably useful categorical organizations. The source that I have been suggesting might exert such an influence is the natural variation of terrestrial illumination, for which we must compensate in order to achieve color constancy. Alternatively, of course, the largely unexplored possibility remains that the intrinsic colors of objects that have been of biological significance for our ancestors may have tended to cluster around the focal colors identified by Berlin and Kay—perhaps, red for ripe fruit (e.g., berries, apples, tomatoes, etc.), green for trees and other vegetation, and blue for water and sky. In the absence of a systematic survey of the spectral reflectance distributions of a large sample of significant surfaces in the natural environment, however, the dimensions of variation of natural illumination may provide for the most parsimonious explanation for the most salient features of the universal color categories of humans.

CONCLUDING REMARKS

The Search for a Nonarbitrary Basis for Psychological Principles

One can distinguish three ways in which we try to establish and to achieve understanding of a psychological phenomenon. Although any combination of these ways can be pursued, simultaneously or in any order, they may tend to become dominant in three successive stages of scientific investigation. The first such stage focuses on the empirical establishment of the phenomenon itself, through behavioral, psychophysical, or linguistic investigations (whether using laboratory experiments or field observations). The second stage shifts focus to the elucidation of the physiological mechanisms that may underlie that established phenomenon, through neurophysiological investigations (whether by electrophysiological recording of concomitant brain activity or by simulation of proposed connectionist models on a computer). The third stage, when indeed it is embarked upon, shifts focus, again, to the problems that the external world poses for an individual. In this stage, we try to understand both the neurophysiological mechanisms and the cognitive and behavioral functions that those mechanisms mediate not as arbitrary design features of a particular species, but as accommodations to pervasive and enduring properties of the world.

In our understanding of the human representation of colors, over three centuries of inspired empirical investigation has established many of the basic phenomena of human color vision. For present purposes, these phenomena have included the constancy, the three-dimensionality, the hue-circularity, and the categorical structure of colors. Beginning later, physiological investigations, which I have not attempted to review, have begun to pin down the neuronal mechanisms underlying a few of these phenomena (see, for example, De Valois, 1973; De Valois & De Valois, 1975; Foster, 1984; Lennie, 1984; Livingstone & Hubel, 1984; Zeki, 1983). The regularities in the world that may determine the nature of these physiological mechanisms, as well as of the perceptual-cognitive phenomena that they mediate, remain largely unexplored. Beyond the long-standing recognition of the problem of color constancy and the model recently proposed for its solution by Maloney and Wandell (1986), I have offered little more than some tentative suggestions about possibly fruitful directions for further exploration.

I began this chapter with the claim that natural selection should lead to the emergence not only of perceptual, behavioral, and cognitive mechanisms that are adapted to the specific circumstances faced by particular species, genders, and domains, but also of mechanisms that are adapted to the general circumstances faced by all so-called higher organisms. Color vision offers a less obvious case for supporting such a claim than the phenomena that I have usually used for this purpose, namely, those of spatial representation (e.g., Shepard, 1984) and of generalization (e.g., Shepard, 1987b). Color pertains to a single sensory modality (vision), whereas space and generalization are not modality specific. Moreover, the properties in the world that might determine the organization of colors are less obvious than those that might determine the representation of space. For example, whereas the three-dimensionality of perceptual space derives directly from the fundamental three-dimensionality of physical space, the three-dimensionality of color space does not so directly or obviously derive from a three-dimensionality in the world. The case for a nonarbitrary basis for the structure of colors, to the extent that it can be made, has the advantage, however, of suggesting that psychological constraints may correspond to regularities in the world even when the correspondence is not initially obvious.

Possible Universal Pressures Toward the Organization of Colors

I conclude with a brief consideration of the sense, if any, in which a tendency toward the properties of color representation I have been considering may be general—or even universal. Throughout, I have spoken of the possibility of selective pressures to which highly visual *terrestrial* animals may be subject in the *terrestrial* environment. I used the qualification "terrestrial" because conditions of illumination in other, for example, aquatic environments can be quite different. Owing to the already noted selective absorption by water of the longer wavelengths, with increasing depth in a marine environment, the available solar light, in addition to being progressively reduced in overall intensity, becomes progressively restricted in spectral range to the shorter wavelengths. This blue shift and compression in range of available wavelengths is known to be matched by a corresponding blue shift and compression in the range of spectral sensitivity of deeper dwelling marine animals (Lythgoe, 1979).

It does seem to me, however, that the wavelength dependencies of the variable height of a sun, presence of atmospheric aerosols, and direct versus indirect illumination might apply quite generally on the surfaces of planets capable of supporting the evolution of highly visual organisms. Such a planet is presumably likely (a) to circle a long-lived star that emits a stable, broad range of wavelengths, (b) to undergo regular rotation about its own axis (owing to the conservation of angular momentum), and (c) to possess an atmosphere that differentially filters the wavelengths of direct and scattered light depending on the (rotationally determined) angle at which the light enters the atmosphere and the size distribution of atmospheric particles. Moreover, the arguments for categorical representation of colors based on memorability and shareability do not depend on particular features of the terrestrial environment. In short, just as there may be universal selective pressures toward mechanisms for the representation of three-dimensional space and for an exponential law of generalization (Shepard, 1987a), there may be quite general selective pressures toward mechanisms for the representation of the surface characteristics of objects in a low-dimensional (perhaps even a three dimensional) color space, with a circular component of hue, and a categorical structure.

Possibly, behavioral and cognitive theorists should aspire to a wider scope for their science. An evolutionary theory of mind need not confine itself to the particular minds of the more or less accidental collection of species we find on planet Earth. There may be quite general or even universal principles that characterize planetary environments capable of supporting the origin and evolution of increasingly complex forms of life. If so, there may be corresponding general or even universal principles of mind that by virtue of their mesh with the principles of these environments, are favored by a process of natural selection wherever it may be taking place.

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