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## 14 It's not really red, green, yellow, blue: an inquiry into perceptual color space

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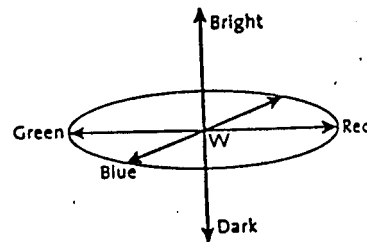
This chapter presents two arguments. The first argument is that, *contra* Hering, Hurvich and Jameson, De Valois, and others, the fundamental chromatic axes of the opponent processes are *not* red/green and yellow/blue. The second argument is that the results found by Berlin and Kay, Rosch, and others, which indicate that particular regions of the color space are selected as the natural locations for color terms, are not due to opponent processes, but to irregularities in perceptual color space. In general, we suggest that alternative theories should be sought as the bases for cognitive models of subjective color experience. To do this we present an overview of commonly used color spaces and scalings of these spaces; we discuss opponent-colors theory and related neurophysiology, and point to some problems with the theory; we examine some empirical phenomena (e.g. additive complements, negative afterimages, etc.) and the possible relation of these phenomena to the organization of color space; we consider unitary hues as relating to color space cardinal axes; and propose a plausible alternative model and discuss its relevance to research in anthropology and psychology.

In the literature addressing the psychological and physiological character of human color vision there is a general account that goes as follows.

(1) Color is organized perceptually in a three-dimensional space as presented in Figure 14.1 below, with red/green (R/G) and yellow/blue (Y/B) as cardinal axes of the space, plus light/dark (white/black for surface colors) as the third dimension. This is the standard diagram presented in numerous articles and texts.

(2) Further, the R/G axis and the Y/B axis of the color space are fixed by and correspond to the output of opponent-process cells measured in the lateral geniculate nucleus (LGN), which are the physiological basis of the subjective sense of purity or uniqueness of the colors red, green, yellow, and blue.

Figure 14.1 Perceptual color space illustrating the dimensions of hue, saturation and brightness, which describe color appearances of light sources. Hue varies around the perimeter of the color circle; saturation varies along the axis joining the central "white point" W to a pure color on the circumference, while brightness varies in the direction perpendicular to the color circle. The perceptual color space for surface color appearance is the same, although in this case one speaks of "lightness" rather than "brightness" (from Lennie and D'Zmura 1988).



(3) Finally, the underlying opponent-process mechanisms explain, at least in part, the evolutionary and developmental history of color terms, with the principal terms for red, green, blue, and yellow developing first in a child's lexicon or in the history of a language, while secondary colors, such as purple, pink, or brown develop later.

These three hypotheses are mutually supporting, and together are offered as a coherent account of a great range of phenomena. However, we think that this account is incorrect, and that the weight of the evidence supports a different set of hypotheses.

### Color spaces

The color space illustrated in Figure 14.1 is just one of the many color spaces that have been constructed by vision scientists. The bases on which color spaces have been developed vary. For example, the CIE space locates colors within a tristimulus coordinate system. This space accurately predicts the effects of the color mixture of lights by the simple addition of vectors (Cornsweet 1970). There are varieties of this space, sometimes called tristimulus spaces (see, for example, Cornsweet 1970: 230, or MacLeod and Boynton 1979). From a psychological point of view, the CIE space has one major drawback: it does not correspond well to perceptual color differences. That is, the distance between different colors in CIE space does not correspond directly to human perceptual judgments of difference and similarity (Indow 1988).

Several other kinds of spaces have been developed. The Natural Color System (NCS) space, for example, was developed by using judgments of the *proportion* of specific color referents contained in color stimuli (Hård and Sivik 1981). The NCS space has the general shape of the space illustrated in Figure 14.1. The color referents – red, green, yellow, blue, black and white (labeled "dark" and "bright" in Figure 14.1) – are considered primary, and all other colors are treated as mixtures of these. Distance in the space from each of the primaries corre-

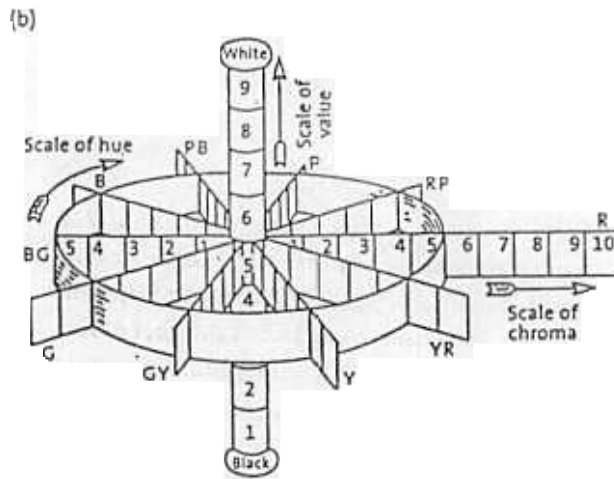
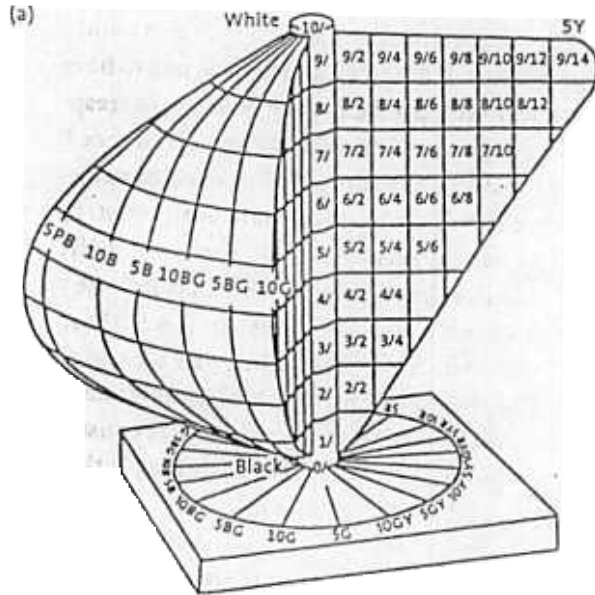
sponds to the proportion of the primary present at that region of the space. Thus a "reddish orange" would be a color that the subject would judge to contain both red and yellow, but to have more red in it than yellow. However, the NCS space does not correspond to direct perceptual judgments of similarity and difference between colors, but rather to estimates of proportions of color subjectively analyzed.

A number of color spaces have been constructed with the goal of having distances between colors correspond directly to the perception of how similar the colors are. We will call these *perceptual spaces*. The Munsell system is one of the best known of these perceptual spaces. It was designed by Albert Munsell, a painter and art educator, to provide a scheme for comparison of colors. The system was first published in 1905, and a renovation of the system was constructed by the Optical Society of America in 1937. The basic idea is that adjacent color samples in each of the three dimensions of color (Hue, Value, and Chroma) should have a constant perceptual difference, so that the color chips are located at equal perceptual intervals along each dimension. However, no method is given for comparing distances along different dimensions. It is as if the distances between levels of lightness were in furlongs, the distance between levels of saturation in stadia, and the distance around the hue perimeter in paces, and no table of equivalences was provided. Illustrations of the Munsell space are presented in Figure 14.2.

Another perceptual color space, the OSA space, was developed by a special committee of the Optical Society of America. It contains a basic set of 424 color samples organized in 3 dimensions. The OSA color samples were constructed with the goal of forming an isotropic space; that is, a space in which perceptual distances between color samples along each dimension are equal. The space is organized in a grid fashion, with each level of lightness having a separate grid. Lightness levels are numbered from +5 to -7, and the grid at each level is defined by two coordinates,  $g$  and  $j$  (roughly, green and yellow).

Other kinds of spaces are also possible, such as spaces in which the judgments about colors are based on affective responses (Adams and Osgood 1973; D'Andrade and Egan 1974; Johnson, Johnson, and Bakash 1986), or based on judgments about the aesthetic quality of combinations of colors, or based on the semantic similarity of color terms (Shepard and Cooper 1992). However, in this chapter we are concerned

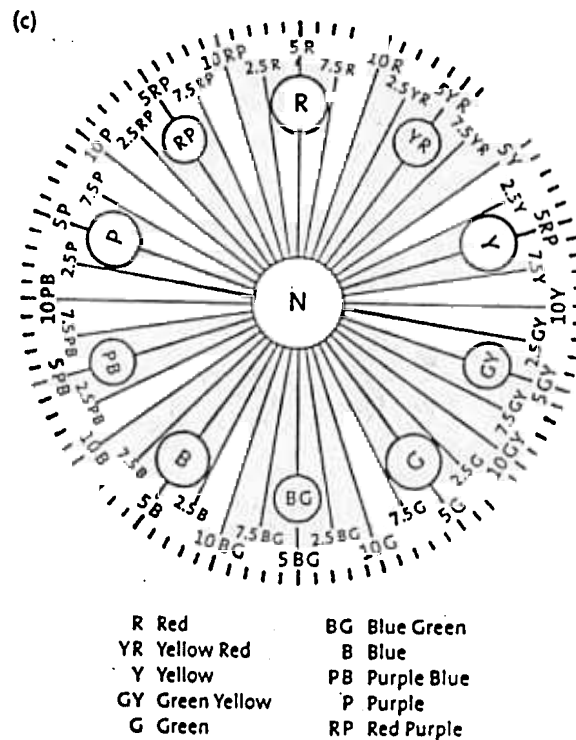
Figure 14.2 (a) Diagrammatic representation of the Munsell color solid with one quarter removed. (b) Cylindrical representation of the Munsell notation system. (c) The Munsell Hue circle (from D'Andrade and Egan 1974).



primarily with color spaces based on psychophysically determined perceptual qualities.

**The scaling of color spaces**

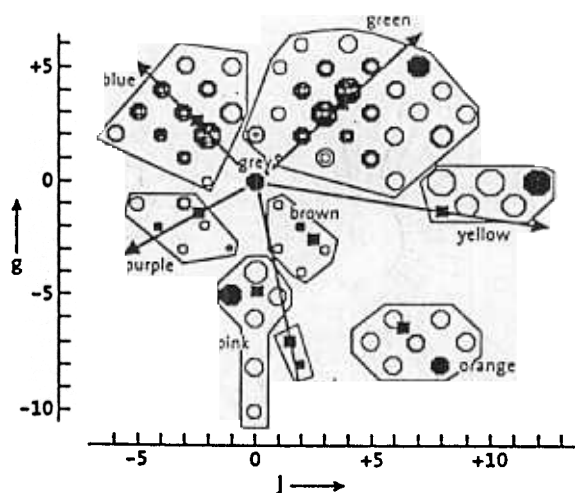
Our first question concerns which of the color systems described above best approximates an imagined perceptual color space in which dis-



tances between samples of colors correspond accurately to subjective judgments of perceptual similarity. A great variety of methods for scaling perceptual judgments of similarity have been employed in color research, including Thurstonian scaling, ratio judgments, and interval judgments. Indow has summarized the results of nineteen different scaling studies, finding an overall pattern which clearly conforms to the Munsell type of organization (Indow and Aoki 1983; Indow 1988).

The major difference between the standard color space illustrated in Figure 14.1 and the Munsell-like space found in the scaling studies summarized by Indow involves the orientation of the axes. These scaling studies do not find an axis where green is opposite red; rather red is opposite to blue-green and green is opposite to red-purple. (Compare Figure 14.1 and Figure 14.2b.) Overall, the results show the color perimeter divided into roughly five equal sections, corresponding to red, yellow, green, blue, and purple. Empirical scaling of the OSA color samples also can be seen to support a five-hue organization with

**Figure 14.3**  
Experimental results for naming OSA color samples. Octagons represent the 128 consensus colors, plotted in the chromatic ( $g$  vs.  $j$ ) plane. Lightness values ( $L$ ) are represented by the size of the octagons, with lightness increasing as octagons become larger. Shaded octagons represent the location of focal color samples. Smaller octagons within larger ones indicate that consensus colors with the same  $g$ - and  $j$ -values are to be found at different lightness levels. The squares show the locations in the chromatic plane only, of color centroids (adapted from Boynton and Olson 1987). See Boynton, this volume.



approximately equal sectors. Boynton and Olson (1987) in a study of consensus in color naming, obtained the English monolexemic names for 424 samples of the OSA set from 7 respondents. These results for the hue perimeter of the color space are presented in Figure 14.3.

The centroids in Figure 14.3 have been computed by averaging the values on each dimension for all color samples called by a particular name weighted by the number of times the sample was so named. Running radial lines from the grey center of the space through FIVE of the centroids (R, P, B, G, Y) gives the angular relations between the color terms, as indicated in Figure 14.3.<sup>1</sup>

About their general results, Boynton and Olson say:

the locations of consensus colors based on this experiment do not agree fully with what seems to have been intended by the OSA committee. In her summary of their work, Nickerson (1981: 9) writes: "Fixing the position of one yellow hue on level  $L=0$  establishes the position of all other hues in accord with the committee's uniform-spacing experimental results . . . blues are thereby located along the negative  $j$  axis, green hues along the positive  $g$  axis, and red hues along the negative  $g$  axis." Our data show that color names cannot be used precisely to describe the chromatic axes . . . Although the use of the symbol  $j$  from French *jaune* to identify the horizontal axis is apt for high lightness levels, it would not be appropriate to refer to a

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yellow-blue axis, because no yellow is seen at low levels of lightness for positive values of  $j$ , and for negative values, although there is one consensus dark blue on it, the axis otherwise divides the blue and purple regions. Similarly, the label  $g$  (for green) poorly denotes the positive end of an axis that tends to divide the blue and green samples almost perfectly into two groups. And pink, not red, lies at the negative end of the  $g$  axis, along which there are not consensus colors at most lightness levels. (1987: 101)

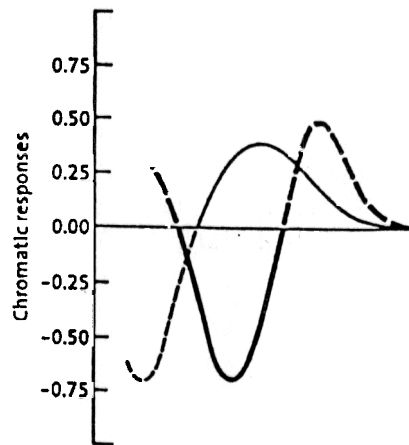
It is significant that the OSA space can be shown to support the five-hue organization, since the position of the color samples was fixed solely by relative perceptual distances, without regard for how these samples might be named. If there was any expectation about the organization of the OSA space, it was that it would look like the four-hue space, as indicated by the Nickerson quote above.

These results do not prove that the cardinal axes of psychological color space are not R/G and Y/B, but they do suggest difficulties for such a position. Why, if pure red and pure green are assumed to be opposing colors in the opponent-process theory sense, are they not found to lie at opposite sides of an achromatic point in empirical scalings of perceptual space? Such a relation seems to be a natural consequence of the theory (see Abramov and Gordon 1994), and seems to be the way in which many color researchers understand both the theory and the relations in Figure 14.1. To explain this kind of discrepancy by postulating additional mechanisms external to a variant of opponent-process theory is reasonable; however, it undermines the usefulness of a strong opponent-colors model as a basis for understanding the cognitive organization of color perceptions.

### Opponent processes

Hering's opponent-color theory hypothesizes two things: first, that the opponent pairs black/white, red/green, and yellow/blue are all that is needed to derive any other color that we can experience; and second, that there are neurophysiological opponent-process mechanisms in the visual system that produce the experience of these primary colors (Hurvich and Jameson 1957). Although modern physiological evidence was not available to Hering, current work

Figure 14.4 Chromatic response functions for a neutral state of adaptation (from Hurvich 1981).



leaves no doubt that cells of the primate visual system do include opponent-type responses to different wavelengths (De Valois 1960; De Valois, Abramov, and Jacobs 1966; De Valois and Jacobs 1968).<sup>2</sup>

A standard diagram to display the way the opponent process might work is presented in Figure 14.4, taken from Hurvich (1981: 201). Basically, the model consists of two response output systems, indicated by the two curves. Within this model, the point at which each curve crosses zero defines a *unique hue*. Thus at about 580 nm the R/G response function is at zero, which means that a normal observer will see a "pure" yellow because the response has neither red nor green in it. Similarly, at approximately 510 nm the Y/B response function is at zero, which means a pure green will be experienced, and at approximately 475 nm the R/G response function is at zero, which means a pure blue will be experienced. Notice that, according to the diagram, there is no single wavelength at which a pure red can be perceived, since both red and yellow outputs occur from 600 nm to 700 nm (the color receptors are unresponsive to light of wavelengths greater than 700 nm or less than 400 nm), and both red and blue outputs occur from 400 nm to 470 nm. This diagram provides an explanation of why pure red is extra-spectral; in order to see a pure red, the yellow component of a 650 nm light must be canceled by the blue component of a 450 nm light so that only a red response occurs (also see Dimmick and Hubbard 1939b).



De Valois and colleagues originally thought that the four types of opponent-process cells they identified in the macaque lateral geniculate nucleus had maximum response peaks and troughs at the wavelengths which people with normal color vision describe as *red*, *green*, *yellow*, and *blue* (De Valois and Jacobs 1968: 538). However, most of the peaks of the recorded opponent-process cells do not appear where one would expect from the theory. For example, according to the graphic figures presented in De Valois, Abramov, and Jacobs (1966), one of the sharpest peaks is displayed by the averaged yellow-plus cells at 600 nm, but this is typically seen as a reddish orange, not yellow. Similarly the peak for the averaged blue-plus cells is around 455 nm, which is a violet. For the green-plus cells the peak is around 540 nm, a yellowish green. Also, the cross-over points of individual opponent cells vary widely (Boynton 1979: 234-237).

These discrepancies undermine the argument that the subjective sense of uniqueness or purity of hues for highly specific wavelengths is determined by the LGN opponent-process cells. In a recent paper, De Valois and De Valois say:

Although we, like others, were most strongly impressed with finding opponent cells, in accord with Hering's suggestions, when the Zeitgeist at the time was strongly opposed to the notion, the earliest recordings reveal a discrepancy between the Hering-Hurvich-Jameson opponent perceptual channels and the response characteristics of opponent cells in the macaque lateral geniculate nucleus (LGN) ... Later investigators also found the same discrepancy, with different stimulation techniques (Derrington, Krauskopf & Lennie 1984; Kaplan, Lee & Shapley 1990), and made the same point. Here we suggest (albeit somewhat belatedly) a third stage of color processing to reconcile this discrepancy. (1993: 1053-1054)<sup>1</sup>

(The third stage of processing proposed by De Valois and De Valois, which produces a set of response functions like those in Figure 14.4, is a hypothesis presented without direct physiological evidence.)

Abramov and Gordon also make the point that the recordings of opponent cells from the LGN do not support the R/G and Y/B hypothesis:

Universal color terms have been explicitly linked to spectrally opponent physiological mechanisms (Ratliff 1976). Specifically, the spectrally opponent and nonopponent cells in the LGN (De Valois et al. 1966) have been used to justify the grouping of white, black, R, Y, G, and B as fundamental terms (Kay & McDaniel 1978; Kay et al. [Berlin and Merrifield] 1991; MacLaury 1992). However, as we have pointed out, *these cells are not hue mechanisms and their detailed response properties should not be used to justify particular linguistic models of the development of color terms.* (1994: 468. Our italics.)

The subjective sense of purity and uniqueness for red, yellow, green, and blue might be determined by physiological events which occur after processing in the lateral geniculate nucleus. However, direct physiological recordings give no support to the hypothesis that red, green, yellow, and blue are the primary axes of the opponent cells. In fact, Abramov and Gordon state:

We now turn to the question of whether there is a necessary pair of perceptual axes that must be used to represent hue space. Stemming from Hering's original work, the accepted bipolar hue axes are RG and YB ... But are these the necessary axes? ... hue cancellation studies demonstrate that hue is organized in opponent fashion: any stimulus that elicits some sensation of G can be added to one eliciting R in order to cancel R ... However, there is no obvious *a priori* justification for these precise axes; *the axes might be chartreuse-violet and teal-cherry, which are approximately the hues to which the LGN cardinal axes point.*<sup>4</sup> Introspectively, however, we find it virtually impossible to think of canceling or scaling all hues in these terms and ultimately this is the principal justification for using RG and YB as axes. (1994: 468. Our italics.)

Thus we find that the physiological recordings from opponent-processing cells in the LGN do not support the R/G and Y/B hypothesis; if anything, they support the hypothesis that the basic axes are the same as those given in Indow's scaling of the Munsell system, oriented roughly around - as Abramov and Gordon would say - cherry/teal and chartreuse/violet.

**A serious problem with opponent-process theory assumptions:  
empirical results for additive complements and unique hues**

To illustrate clearly one specific way opponent-colors theory conflicts with empirical data, we present three opponent-colors theory assumptions below which explicitly state the relationships between the theory, unique color appearances, and visual system neural responses.

**Assumption 1: unique color appearance and visual channel response**

There are two chromatic channels used in coding color appearance (hereafter "light"): the red-green and yellow-blue channels.

A light that has zero output on the red-green channel is blue, yellow, or white in appearance.

A light that has zero output on the yellow-blue channel is red, green, or white in appearance.

Each light produces either a positive, zero, or negative output on the red-green and yellow-blue channels. (Thus, a light that appears either bluish or yellowish has a non-zero output on the yellow-blue channel, and a light that appears either reddish or greenish has a non-zero output on the red-green channel.)

**Definition 1: unique chromatic appearances**

*Unique red* is a light that has zero output on the yellow-blue channel and is red in appearance.

*Unique green* is a light that has zero output on the yellow-blue channel and is green in appearance.

*Unique yellow* is a light that has zero output on the red-green channel and is yellow in appearance.

*Unique blue* is a light that has zero output on the red-green channel and is blue in appearance.

*Unique white* is a light that has zero output on both the red-green and the yellow-blue visual channels and is achromatic in appearance.

In the literature, Assumption 1 and Definition 1 are accepted as naturally stemming from Hering's notions of unitary and psychologically simple chromatic attributes, and it is also accepted that these

attributes represent antagonistic or opponent pairs (Jameson and Hurvich 1955: 548; Krantz 1989: 279-80).

The color appearances described above can be combined in various ratios to produce different appearances. Below, Assumption 2 explicitly states some of the possible chromatic response relations for mixtures of unique appearances that are assumed by opponent-colors theory. (For brevity, below we consider only some of the cases for combining red and green stimuli at yellow-blue equilibrium.)

#### Assumption 2: additive mixtures of unique-appearance lights

Suppose  $L_1$  and  $L_2$  are two different lights that both have zero output on the yellow-blue channel. If  $L$  is the light that is produced by superimposing (hereafter *adding*)  $L_1$  and  $L_2$ , then  $L$  must also have zero output on the yellow-blue channel.

Historically, this assumption of linear additivity, generally referred to as "linearity," has been an important property of the opponent-process model because it permits prediction of chromatic response functions from spectral light mixtures (see Judd 1951; Hurvich and Jameson 1957; Krantz 1989: 286).

For Assumption 2 to be deemed a reasonable assumption it must be validated through empirical tests of additive mixtures of  $L_1$  and  $L_2$ , yellow-blue equilibrium lights. The underlying rationale is to have the opponent theory be a simple extension of Grassmann's laws (see Wyszecki and Stiles 1982: 118). If Assumption 2 were found to fail empirically then the relation between the standard model (i.e., the Grassmann structure underlying the CIE tristimulus space) for color mixtures of spectral lights and the opponent-process model becomes complicated and requires Assumption 2 to be modified to specify the exact form of the nonlinearity.<sup>5</sup>

#### Assumption 3: complementary additive light mixtures

If  $L_1$  is a unique green light with zero output on the yellow-blue channel, then there exists a reddish light  $L_2$  that has zero output on the yellow-blue channel such that when  $L_1$  and  $L_2$  are added to yield light  $L$ , then  $L$  has zero output on the red-green channel. (By Assumption 2  $L$  has zero output on the yellow-blue channel also, thus  $L$  will

appear white.) In this case,  $L_2$  is called an *additive complement* of  $L_1$ .

Assumption 3 clearly follows from the theory formulated in the literature. For example, Jameson and Hurvich (1955: 548) state:

The chromatic response of the visual system for a given hue is assumed to be proportional to the amount of the opponent cancellation stimulus necessary to extinguish that hue. To measure the amount, say, of yellow chromatic response evoked by a spectral test stimulus perceived as yellow, whether pure yellow, red-yellow, or green-yellow, the experimenter adds to the test stimulus a variable amount of blue stimulus (e.g. 467 nm) until the observer reports that the yellow hue of the test stimulus is exactly canceled. In other words, the observer's endpoint is a hue (or a neutral sensation) that is neither yellow nor blue.

An extension of this idea implies that a "neutral" sensation is tantamount to a phenomenological "white" experience. This idea was generalized and used to define "complementary" pairs of stimuli. As Hurvich (1981: 49) states, "pairs of wavelengths that generate a white experience when intermixed are known as complementary wavelengths."

#### Theorem 1

Assumptions 1, 2 and 3 imply that each additive complement of a unique green is a unique red.<sup>6</sup>

Theorem 1 is a special case of a point central to opponent-colors theory as stated by Hurvich: "Once we realize that the whiteness aspect is simply the uncanceled excitation produced by both stimuli of the complementary pair, we need only seek out two stimuli in the spectrum whose chromatic excitations are opposite and equal in order to find stimuli properly characterizable as complementary" (1981: 70).

However, when interpreted phenomenologically, the conclusion of Theorem 1 fails empirically. As early as 1907 Hering's student, A. von Tschermak, reported that "under usual conditions of observation, in order to produce a colorless appearing mixture [of lights] one needs for a unique (*urfarben*) red not a pure green but a somewhat bluish-green" (Tschermak 1907: 478). Others have subsequently also verified that unique red and unique green, when superimposed to produce a

non-reddish and non-greenish color, always produce a yellowish appearance (e.g. Dimmick and Hubbard 1939a, 1939b; Judd 1951; Burns, Elsner, Porkorny, and Smith 1984).<sup>7</sup>

Thus, there is a defect in the theory and further postulating that a yellow appearance is an acceptable "neutral sensation" for red and green mixtures does not abrogate the problem because, by Theorem 1, at least one of the essential assumptions stated above remains incorrect.<sup>8</sup>

Although the above empirical results for mixtures of unique red and unique green are known by many color-vision experts, it is still often implied by theories presented in the current literature (e.g. De Valois and De Valois 1993) that the zero-output cross-over points in chromatic response functions correspond to unique hues that additively combine to yield *neutral* sensations. De Valois and De Valois (1993: 1060) say: "Unique blue and yellow occur at the cross-points of the red-green system, and unique green at the cross-point of the yellow-blue system . . . The fourth hue, red, is extraspectral, at a combination of short and long wavelengths which would just cancel the yellow-blue function." However, for the case of *unique* red and unique green this is empirically false.

The failure of Theorem 1 is a serious problem for opponent-process theory that can never be patched up as long as unique hues are maintained as unitary sensations and antagonistic channel zero-crossings. In light of these facts it seems wise to pursue alternate hue axes that model the empirical data more closely, and we suggest that one such model may be provided by a maximized interpoint-distance formulation in, for example, the Munsell color space, or in some other perceptual scaling space.

### Additive complementary colors and afterimage complements

Given the above-mentioned conflict between observed empirical relations and opponent-colors theory, one question is naturally raised: how do the additive complements defined by light mixtures (as opposed to defined by a theory) relate to the Munsell or OSA surface spaces?<sup>9</sup> Nickerson prepared a series of charts which locate the Munsell system within the standard CIE diagram (Wyszecki and Stiles 1982, appendix 6.6.1). These charts indicate that the Munsell color

perimeter (see Figure 14.2c) gives a reasonable approximation to the empirically observed structure of the additive complements in the sense that such complements are found at points diametrically opposite the achromatic center. (As defined by Schrödinger, "complementary colors . . . lie on a line on the chromaticity diagram that intersects the position assigned to white" [Niall 1988: 83].

Complements when mixed in suitable proportions yield a color match to some achromatic stimulus [Wyszecki and Stiles 1982: 176].) This approximation of the Munsell hue perimeter to the empirically observed relations of additive complementary hues is not discussed in the existing literature.

What does the correspondence between the Munsell space perimeter and the structure of the additive complements tell us? Given that the *true* axes representing actual opposing color-pair relations are aligned somewhere within the five-hue circle of the Munsell space (say, towards cherry/teal and chartreuse/violet), then one would expect hues on opposite sides of the circle to be additive complements, since they would, by definition, have "equal but opposite" response outputs.<sup>10</sup>

This line of argument is also supported by the structure of negative afterimage hues. Afterimage hues, produced by fixating one's gaze for several seconds on a color stimulus and then looking at a blank colorless surface, are a well-known and much-studied phenomenon. Negative afterimages correspond fairly closely to the empirical additive complements for all but yellow-blue pairings (Wilson and Brocklebank 1955; Bagley and Maxfield 1986). Thus the afterimage data accord with empirically observed complement relations, and both suggest a space with the Munsell-like axes we mentioned, rather than cardinal R/G and Y/B axes.

Moreover, using a paradigm that assessed thresholds for detecting changes in color stimuli, Krauskopf, Williams, and Heeley (1982) provide an interpretation of findings consistent with opponent-process theory axes, although they empirically found a tritanopic confusion line, and not the Y-B cardinal axis, as a direction in color space carrying signals along "separate, fatiguable, second stage pathways," making it distinct from other possible directions in the space, and suggesting an alternative cardinal direction. Although Krauskopf *et al.* do not suggest it, the results of this careful study seem to justify exploring and testing alternative color space models.

### The basic hues

There is an experimental literature which shows that some hues are *elemental* – that is, they cannot be perceptually analyzed into more basic hues. In one kind of experiment, subjects are asked to give the percentage of some specific hue “directly experienced” when viewing a stimulus color. If there is a region of the hue perimeter which is described by the term for this hue, and no other hue terms are applicable to this region, the hue is elemental. For example, there exists a region of the hue perimeter which can only be described as *yellow*, and which is experienced as pure yellow in that it has no red or green in it. In various studies, red, yellow, green, and blue have been demonstrated to be elemental for at least some subjects (Sternheim and Boynton 1966; D. L. Miller and Wooten 1990). These “elemental” hues are usually taken to represent end-points of opposing pairs which define the relations among colors on the hue perimeter and the axes of color space.

The idea that the hue perimeter of color space is defined by the dimensions red–green and yellow–blue is relatively old. Waller in 1686, Hofler in 1886, Titchener in 1887, Ebbinghaus in 1902, Hering in 1911, Boring in 1929, and Plochere in 1948 all presented diagrams with red and green, yellow and blue as opposites (see Gerritsen 1975). For some reason, from Waller on, the hue perimeter was diagrammed not as a circle but as a square (except by Hering and Plochere). There was another tradition, starting with Goethe in 1793 and Herschel in 1817 in which the hues were arranged around six points, or three “complementary” pairs, with red opposite green, yellow opposite violet, and orange opposite blue.

The data collected by Sternheim and Boynton (1966) and D. L. Miller and Wooten (1990) support the intuition that red, green, yellow, and blue have a special “landmark” status as colors. This special status is hypothesized to result from R/G and Y/B opponent-process neurophysiology. However, we will argue below that this special status could be derived from irregularities in the perceptual color space. Some of the variability in findings concerning exactly which hues are opposite each other in the color space, reflected in the different color spaces proposed over 300 years, may also be due to limitations on judgments of similarity and difference for colors. It has been found that estimates



of similarity between any 2 points in color space become indeterminate when the perceptual distances are large. Indow (1988: 461) says: "it is true that two colors such as [Munsell] 5R 4/14, 5G 5/8 [a focal red and a focal green] simply appear 'entirely different,' and the perceptual difference in these pairs is not intuitively palpable as in more moderate color differences. There seems to be a limit within which the impression of difference naturally takes place." Thus one cannot determine by direct perceptual comparisons whether green, blue-green, or blue is opposite, or "complementary," to red. The color scaling space is constructed by having a series of overlapping judgments, building up a global map from many local maps. The technology to accomplish this was not available to early color researchers.

In an analysis of psychologically basic hues in surface colors Indow (1987) compares a four-basic-hue model (i.e., R, G, Y, B) with a five-basic-hue model (i.e., R, G, Y, B, P) and finds that the fit of the five-hue model to the empirical data is better: "when P [purple] is not included, individual differences in R and B become much larger" (p. 255 and his Figure 2). Thus, "though P [purple] is not unique [by a non-reducibility criterion] it seems to help sharpen concepts of pure red and pure blue" in a vector representation of unique hues.

Indow's (1987) comparison of chromatic response curves illustrates that these can be represented equally well by either five hues or four. What is clear is that psychophysically there is no reason not to use five hues in representing data except that the criteria of "non-reducibility" is not upheld. The question raised is what are the compelling reasons for taking non-reducibility as the criterion for determining basic hue points? It seems that the need to link neural physiology with purity of primary color perceptions motivates the use of this criterion, but given the present inchoate state of color vision neurophysiology it seems that the main support for the four-basic-hue model is intuitive appeal and historical continuity.

### The evolution of color terms and the irregularity of the perceptual color space

Berlin and Kay (1969) have presented much evidence suggesting color terms can be ordered in an evolutionary sequence. It has been hypothesized that opponent-process mechanisms play a role in bringing this

about (Kay *et al.* 1991:14). If, however, the privileged position of red, green, yellow, and blue as opponent-process hues is denied, how can the evolution of color terms be understood?

One possible explanation is that the developmental order of color names is due to the irregular shape of the color space. The best way to illustrate the irregularity of the perceptual color space is to examine each of the hues as they are laid out on the pages of the *Munsell Book of Color*. This can also be seen in Figure 14.2a where the shape of the color solid deviates markedly from that of a sphere. Hue interacts with saturation and lightness to produce several large "bumps"; one large bump is at focal yellow, and another at focal red. The entire blue-green area is depressed (i.e., of low Chroma), as is the area below focal yellow. These "bumps" are not simply due to constraints imposed by restricted surface color-printing gamuts. Analogous color-space bumps are found when a light-mixture space is considered.

We assume that the names that get assigned to the color space at any one stage are likely to be those names which are most informative about color. If one has only two color terms, the most informative system is one that places the referents of the terms at the maximum distance from each other. A dark/cool versus light/warm division of the color space accomplishes exactly this. Once the light/warm versus dark/cool division has been made, the region of color space that is most distant from the regions specified by these two terms is red. After these three terms are in place, it becomes more difficult to determine which is the next most distant region because the differences in distances are smaller and depend in part on how the focal areas are determined. Based on the distances between centroids in the OSA space computed by Boynton and Olson (1987), one would expect either yellow or blue to be the next split, followed by green, purple, pink, orange, brown, and grey. This kind of interpoint distance model would generally predict the results found by the World Color Survey (see Maffi 1988).

This notion is also supported by recent empirical work (Smallman and Boynton 1990, 1993) which shows that performance in a visual search task is the same whether subjects employ individual sets of personal "nonbasic" colors or a standard set of similarly spaced "basic" colors for coding stimuli. The conclusion drawn, which questions the status of Berlin and Kay's eleven basic colors as neurologically based

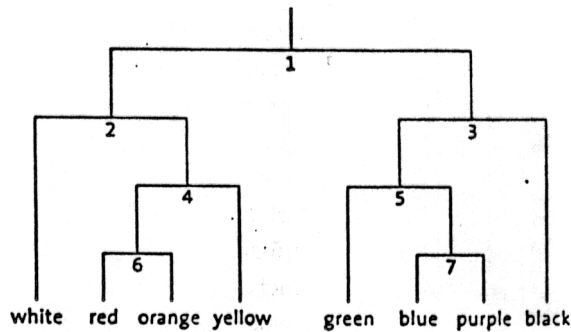
*perceptual fundamentals*, is that "basic colors segregate well not because they are universally named but because they are well separated in color space" (1990: 1985). Whether additional criteria for determining color codes (for example, an individual's favorite color set) might give rise to performance improvements in a visual search task is an interesting question.

Thus, the general argument we are presenting is that the irregularities of the perceptual color space give an informational advantage to making the divisions so that category foci are maximally different from each other. These irregularities also make certain regions of the color space more perceptually salient than others, primarily because such regions achieve a great saturation. The yellow and red peaks of the Munsell space, for example, are highly salient, with extremely high saturation levels. Blue and green have less notable peaks, but are still distinctive. In our account, we consider it plausible that the large number of studies which show that categorization, or memory, or focal naming are not random across color space suggest that people are using the *perceptual* structure of the stimulus space which is directly available to them.

A model for this general process can be found in an experiment by James Boster (1986). Boster selected focal color chips for red, orange, yellow, green, blue, black, and white. Subjects were asked to sort these color chips into two groups on the basis of similarity: "Imagine you speak a language which has two color words, how would you choose to divide up the colors and which colors would you put together into each group?" After the first sort, subjects were then asked to subdivide each of the two groups they had created, and then to subdivide again until all the chips were separated. The mean taxonomic tree for all subjects is presented in Figure 14.5. The successive divisions of this tree correspond closely to the Berlin and Kay evolutionary stages discussed above. The interpretation we offer is that the Berlin and Kay evolution is obtained not because the first six elements represent "fundamental neural response categories" (Kay *et al.* 1991) but because successively these elements maximize the information in the perceptual color space.

Since we are using the irregularities of perceptual color space to attempt to account for a variety of phenomena, it would be helpful if there were some clear explanations for these irregularities. This, how-

**Figure 14.5** Taxonomic tree representing the overall group structure for successive divisions of color samples. Numbers indicate the average order in which clusters of samples were split (adapted from Boster 1986).



ever, is beyond our expertise – although one should note that not even in the world of feathers and flowers has anyone found a highly saturated dark yellow, or a blue-green that is as saturated as focal red. It would appear that the ratio of chromatic to achromatic responses, which varies by wavelength, plays a role in explaining the saturation differences across hues (Hurvich and Jameson 1957; Hardin 1988: 114–116).

### Red, green, yellow, and blue in cognitive psychology research

It turns out that while psychophysicists have for a long time known about the many discrepancies between accepted opponent-colors theory and the empirical phenomena (e.g. Judd 1951), this has not reduced use of the model in cognitive psychology research. We have found that the cognitive psychology literature often invokes unproven assumptions about the relation between visual neurophysiology and subjective experience. Many examples of this can be found in psychology textbooks and scientific research articles. For example, investigations of the universality of color terminology and color memory have widely employed the opponent-hue neurophysiological model as a basis for predicting that the hues red, green, yellow, and blue should be empirically distinguished from other, less-fundamental, hues (e.g. Rosch 1972; Rosch 1973; Varela, Thompson, and Rosch 1991; Kay *et al.* 1991). Research in developmental psychology has also widely employed the four-opponent-hue model. Bornstein, Kessen, and Weiskopf (1976) tested whether at 4 months of age infants can discriminate and categorize color stimuli into “the four basic qualitative

categories." In an extensive study of children's color naming, Cook (1931) tested over 100 2- and 6-year-olds in naming and matching red, yellow, green, and blue stimuli. In construction of intelligence tests Binet and Simon (1908/1916) required children to identify correctly all four "fundamental colors, red, blue, green, and yellow." Additional studies in which the standard opponent-colors model is employed as a rationale for hypothesis testing and stimulus selection are Johnson (1977) and G. A. Miller and Johnson-Laird (1976).

In addition to the examples cited here many other recent instances can be found in the cognitive psychology literature. In considering this literature we have found that the R/G and Y/B opponent-color model has been employed as a foundation for the construction of a color atlas; as an explanation for the subjective sensations of color experience; and as a rationale for cognitive model construction, stimulus selection, and the interpretation of results in investigations of the psychological color space. In view of the empirical evidence discussed above, we suggest that the use of the four-hue opponent-process model in these ways is unwarranted.

Moreover, we feel no strong test of the validity of the four-hue model as a basis for *cognitive* phenomena has been carried out in the existing research, and that most investigations have used the model, with all its assumptions, because it was a priori considered as a natural and valid basis for explaining higher-level cognitive phenomena. We have seen that often the psychological tests of opponent-process relations are conducted in such a way that the model is not really challenged.

### Summary

The account we propose is as follows.

- (1) Color is organized perceptually in a three-dimensional space which corresponds closely to the Munsell and OSA systems.
- (2) This space is organized so that additive complementary hues are approximately opposite each other.
- (3) Color matches to negative afterimages show a similar pattern, but there appear to be small anomalies in the Y/B region.
- (4) These results are what one would expect if the opponent-processes

axes were cherry/teal and chartreuse/violet, or some simple rotation of these axes.

- (5) The hypothesis that opponent-process neural mechanisms in the retina give rise to a perceptual space with R/G and Y/B axes is not empirically supported in that the unique hues cannot be both cross-over points and additive complements.
- (6) The major support for the R/G and Y/B hypothesis is the subjective impression that these hues are "pure." The special salience of certain colors may be due to the irregular shape of perceptual color space.
- (7) There is some support for the hypothesis that the evolution of color terms is based on a process whereby terms introduced into a language tend to be maximally distant in perceptual color space from already existing terms.
- (8) The use of the R/G and Y/B opponent-process hypothesis as an explanation of various findings about the non-arbitrary nature of color memory, or color naming, or color categorization, is not warranted on the basis of present knowledge.

## Notes

<sup>1</sup> Running radial lines through the centroids of the five hues suggested, rather than all centroids presented in the data, gives an empirical space partitioned by roughly equal sectors, whereas subdividing the scaling using only the four standard hues (R, B, G, Y) leaves a large gap in the space between blue and red. Alternatively using six or seven centroids also yields sectors of unequal area (although the use of the orange centroid is possibly an acceptable division in this particular space). The point we emphasize is simply that there is a close structural correspondence between this perceptual scaling of the OSA stimuli and the structure of the Munsell color solid – they both present a considerable area devoted to blends of red and blue stimuli. The Munsell system's structure is given via five (R, P, B, G, Y) reference points rather than the opponent-colors theory standard four colors. It is interesting that the OSA system (constructed by researchers with opponent-colors theory in mind) when perceptually scaled does not yield orthogonal R/G, Y/B axes as opponent-colors theory might predict, but approximates a Munsell-like spatial organization. Convergent findings like these may suggest an alternative frame for thinking about models of color space and axes in that space.

<sup>2</sup> Both non-human primates and humans have opponent-type visual neurophysiology. However, generalizing results from neurophysiological studies of other primates to humans is problematic for evaluating *phenomenological* experiences like the subjective color sensation of humans.

<sup>3</sup> De Valois and De Valois acknowledge the work of G. E. Müller and D. B. Judd for first presenting the essential features of their proposed three-stage model.

<sup>4</sup> The term "cherry" describes a bright red; "teal" is a greenish blue; "chartreuse" is a greenish yellow; and "violet" is a deep purple.

<sup>5</sup> According to Krantz (1989), Hurvich and Jameson extended their theory to deal with problems of empirically observed non-linear relations (e.g. Bezold-Brücke phenomena). However, as Krantz notes, the nonlinearities suggested in the Hurvich and Jameson extended theory do not explain the nonlinearity of the yellowness/blueness equilibria (p. 289).

<sup>6</sup> Proof: suppose  $G$  is a unique green light. Then  $G$  has zero output on the yellow-blue channel by Assumption 1

and Definition 1. By Assumption 3, let  $r$  be a reddish light with zero output on the yellow-blue channel such that the combination of  $g$  and  $r$  yields a light  $w$  that has zero output on the red-green channel. By Definition 1,  $r$  is unique red. By Assumption 2,  $w$  must also have zero output on the yellow-blue channel. Therefore, by Definition 1,  $w$  is unique white.

7 The Burns et al. (1984) study is careful and thorough in its test of opponent-process ideas and shows that an equillumiance mixture of unique green and unique red would appear yellowish for  $2^\circ 40'$  field sizes. They conclude: "our data rule out general linear models which have unique hues as balance points for either of the two opponent mechanisms" (p. 487).

8 Larimer, Krantz, and Cicerone (1975) have also empirically shown that increases in the luminance of an otherwise fixed red light which appears neither bluish nor yellowish produces "a striking increase in apparent yellowness" of the red light (p. 726). This can be viewed as a violation of Assumption 2 above.

9 An assumption inherent in this discussion is that color relations found in color cancellation studies (e.g. Hurvich and Jameson) should agree, to a large extent, with color relations found via perceptual scaling judgments (e.g. Indow or Boynton). By agree we mean that at the very least the relational structure of cancellation results should be structurally similar to the relational structure of perceptual scaling results. For example, if in a cancellation paradigm a monochromatic yellow light is found to exactly cancel a monochromatic blue light, then we would expect a similar structural relation for opposing colors to be approximated in the spatial organization of empirically determined perceptual distance judgments, in additive and complementary color relations, and perhaps in the organization of other cognitive color processing. We consider the existing cancellation results an important demonstration of underlying processes and thereby a limiting condition, or starting point, for models describing more complex color perception phenomena. Beyond "isomorphic" correspondence, it would be a happy coincidence if it is found that linear relations observed in cancellation data are also preserved in perceptually scaled colors connected by a straight line and which occur on opposing sides of a neutral achromatic point.

10 The CIE space was constructed to permit additive, or cancellation, pairs to be defined as corresponding points along a straight line through the achromatic "white" point. However, drawing a straight line through the white point of a perceptual space, like Munsell, to find

complementary pairs is somewhat different. That is, there is no a priori reason why surface "complements" should correspond to CIE cancellation complements. While the two spaces are topologically isomorphic, it is not logically necessary that their linear structures are isomorphic. To what extent then do the color-pair relations in the two kinds of spaces coincide? As mentioned earlier, Newhall, Nickerson, and Judd (1943) demonstrated that, when compared to an early version of CIE space, an adjusted Munsell space gives an approximation to the equispacing achieved in the CIE formulation. Indow (1987) points out that portions (i.e., the Y-B relation) of the Munsell scaling obtain opposing pairs of corresponding colors via a linear locus through the CIE white point. Deviations from strictly linear complement relations are attributed in part to Abney and Bezold-Brücke hue shifts (see Indow [1987] Figure 4, p. 258). Moreover, Indow (1987), citing Krantz (1975), states: "perceptual color differences and principal components, both obtained through subjective judgments, approximately behave as a linear system" (p. 259). This correspondence of CIE space with perceptual space needs further exploration to determine fully which metric relations, if any, are preserved in both spaces.

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