

## Subjective and Objective Scaling of Large Color Differences

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The notion of "psychophysics beyond sensation" can be understood in at least two different ways: (a) as an extension of sensory psychophysics to complex psychological processes involving memory, semantics, etc. and (b) as an application of psychophysical methods to objective neurophysiological processes, such as event-related potentials and spike discharges. It is the second meaning that we focus on in this work. We think of psychophysics as being incorporated within the framework of generalized neuroscience, where both cognitive and executive processes are studied by both neurophysiological and psychophysical methods. The construction of color spaces by means of multidimensional scaling provides a good example of this integrated approach.

### SPHERICAL MODEL OF COLOR DISCRIMINATION

The idea of measuring subjective distances among stimuli is one of the most fundamental ideas in psychophysics. There are two main approaches to this issue. One is to try to compute the subjective distances from some measure of an observer's ability to discriminate very similar stimuli, those that can be easily confused.

Fechner was the originator of this approach, and its modern version can be found in Dzharov and Colonius (1999, 2001). Another approach is to compute the subjective distances from various measures of dissimilarity obtained from people or animals facing pairs of clearly different stimuli, those that cannot be confused. With the second approach, irrespective of whether one uses direct numerical estimates of dissimilarities given by humans or amplitudes of evoked potentials obtained (in humans or in animals) in response to abrupt stimulus changes, the results can be presented in the form of a matrix whose rows and columns represent the same set of stimuli whereas the entries contain all pairwise dissimilarities among them. The technique for dealing with such matrices (which can be called matrices of large differences) is known as multidimensional scaling (MDS). The dissimilarity values within such a matrix are viewed as monotonically related (within statistical variation) to geometric distances among points representing stimuli in a psychophysical space. The goal of MDS is to reconstruct this space (Torgerson, 1958). In this chapter we describe how MDS leads to the reconstruction of the color-discrimination space.

The MDS analysis of dissimilarities among monochromatic lights varying in wavelength and luminance shows that, if these dissimilarities are interpreted as monotonically related to Euclidean distances, then the color points form a four-dimensional geometric configuration (Izmailov & Sokolov, 1991). An essential feature of this configuration is that the color points do not fill in the four-dimensional space densely, but rather form a surface of a constant positive curvature in this space, a four-dimensional sphere. The position of a point on this sphere is characterized by three spherical coordinates, each corresponding to one of the three subjective characteristics of color: hue, saturation, and brightness.

This is a remarkable finding when compared with the traditional view that only three Cartesian dimensions are sufficient to describe the color space and that color points comprise a three-dimensional solid in this space. This traditional model is based primarily on color-mixture data and threshold measurements. It has been noted, however (Izmailov, 1980; Judd, 1967), that estimated distances among colinear points in the three-dimensional color solid are not additive. The spherical model shares with the color solid the traditional triad of subjective color characteristics (hue, saturation, and brightness), but their geometric status changes from that of Cartesian coordinates to that of spherical coordinates (Izmailov, 1995). Correspondingly, the number of the Cartesian coordinates in the spherical model increases from three to four. It is from these coordinates (rather than the three spherical ones) that one computes the intercolor differences as the Euclidean lengths of the chords connecting the color points lying on the four-dimensional spherical surface:

$$d(X, Y) = \sqrt{\sum_{k=1}^4 (X_k - Y_k)^2}, \quad \sum_{k=1}^4 X_k^2 = \sum_{k=1}^4 Y_k^2 = 1, \quad (1)$$

where  $X_k, Y_k (k = 1, 2, 3, 4)$  are the Cartesian coordinates of the colors  $X, Y$ .

The first two Cartesian coordinates have a clear neurophysiological interpretation: They are interpreted as outputs of two color-opponent channels reacting to the spectral distribution of light (see Fig. 2.1). The first Cartesian coordinate ( $X_1$ ) represents the output of the red-green channel, the second one ( $X_2$ ) the output of the blue-yellow channel. Taken together, these two coordinates determine the color hue by the angle  $\alpha$  on the chromatic plane  $X_1X_2$ , defined as

$$\frac{X_2}{X_1} = \tan \alpha.$$

This interpretation agrees with the traditional view that the spectral distribution of light maps onto the color hue through the two color-opponent channels. Note that, when considered separately, the outputs of the red-green ( $X_1$ ) and blue-yellow ( $X_2$ ) channels change as cosine and sine functions, respectively, of the angle representing hue:

$$X_1 = a \cos \alpha, \quad X_2 = a \sin \alpha, \quad (2)$$

where  $a$  is a positive constant.

The interpretation of the remaining two Cartesian coordinates ( $X_3, X_4$ ) is similar, although more subtle neurophysiologically (see Fig. 2.2). Clearly they encode the brightness of light, but this is not done by either of these coordinates taken separately. Rather, in a complete analogy with how the hue is encoded by the color-opponent channels, the brightness of a color is represented by the angle  $\beta$  of the color point in the brightness plane  $X_3X_4$ , defined as

$$\frac{X_4}{X_3} = \tan \beta.$$

Taken separately, the coordinates  $X_3$  and  $X_4$  are assumed to represent the outputs of the nonopponent dark ( $X_3$ ) and bright ( $X_4$ ) channels, consisting of the off-cells and on-cells, respectively, of the visual system (Jung, 1973). Again, geometrically  $X_3$  and  $X_4$  change as cosine and sine functions, respectively, of the angle representing brightness:

$$X_3 = b \cos \beta, \quad X_4 = b \sin \beta, \quad (3)$$

where  $b$  is a positive constant.

To summarize, the visual system extracts from the light flow its two principal characteristics, the spectral distribution and the overall intensity. Each of these characteristics is encoded by a pair of channels that work in an interdependent fashion, so that the output of one of the dual channels is inversely related to the output of the other. Specifically, this reciprocity in the model works in the cosine-sine fashion, ensuring that the outputs of the dual channels form a circular trajectory in a plane (Izmailov, 1997; Sokolov & Izmailov, 1983, 1988).

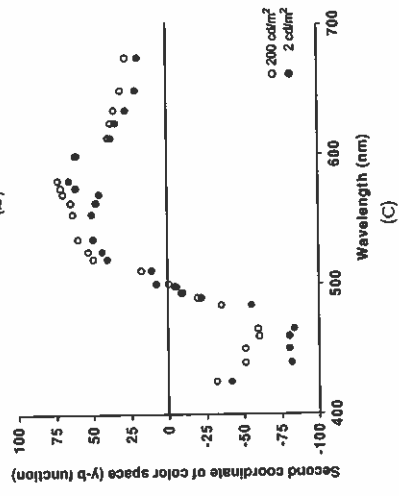
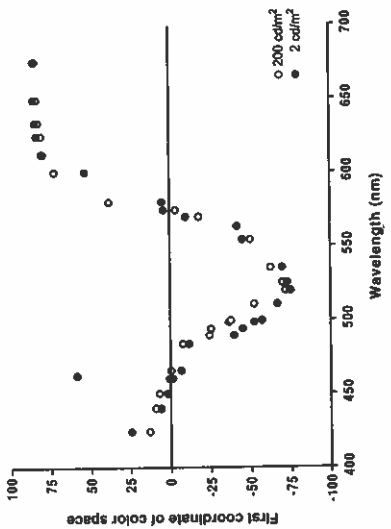
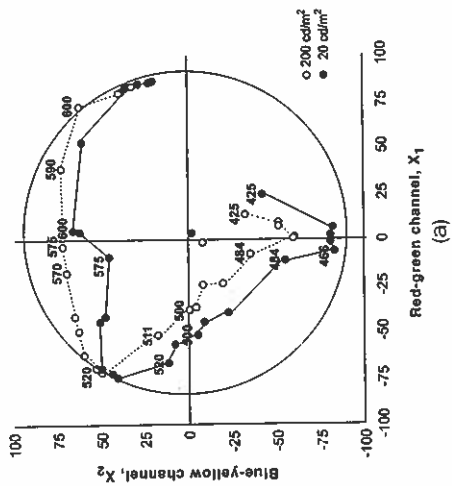


FIG. 2.1. (a) Projections of color points on the chromatic plane ( $X_1, X_2$ ) of the four-dimensional color sphere. Filled and open circles represent monochromatic stimuli varying on two levels of luminance. (b), (c) Red-green ( $X_1$ ) and blue-yellow ( $X_2$ ) opponent functions derived from the spherical model of color discrimination.

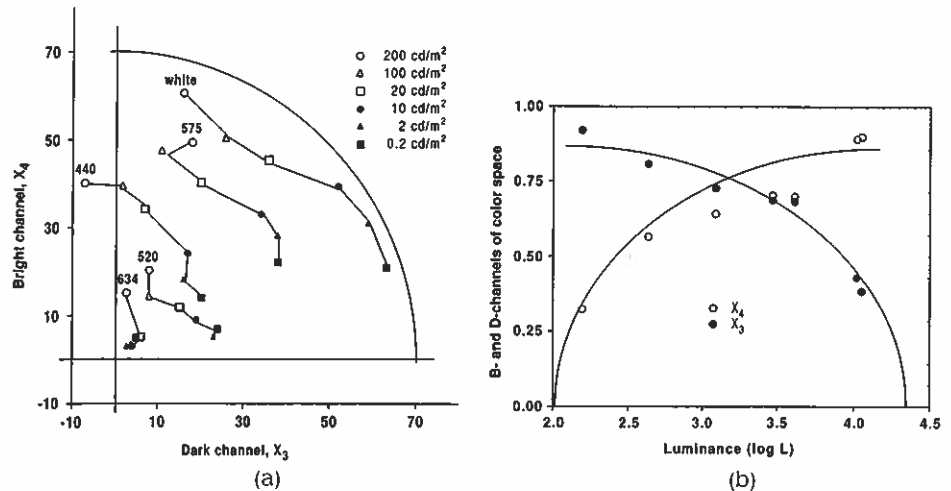


FIG. 2.2. (a) Projections of color points on the achromatic plane ( $X_3X_4$ ) of the four-dimensional color sphere. The colors shown are monochromatic and change on six levels of luminance, represented by six symbols connected by a solid curve, with the attached number indicating the wavelength in nanometers (b) Two achromatic coordinates of color space as functions of stimulus luminance. They are interpreted as dark ( $X_3$ ) and bright ( $X_4$ ) channels of visual system.

The reader may have noted that this description, although involving all four Cartesian coordinates of the color space, does not mention saturation. This is not an oversight, as we believe that saturation has a status different from that of hue and brightness. To produce the latter two is the primary function of the respective pairs of dual channels,  $X_1X_2$  for hue and  $X_3X_4$  for brightness, and they reflect separate physical properties of light, spectral distribution and luminance, respectively. In this sense one can consider these color characteristics as "natural" (or "primary") sensory phenomena. By contrast, we suggest that saturation results from a network interaction between the two color-processing dual mechanisms, and it does not reflect an independent physical property of light. In this sense saturation can be viewed as an "artificial" (or "secondary") characteristic of color. That is why its dependence on various physical parameters of light is very complex (Judd, 1951).

In the spherical model of color vision the network interaction between the two dual-channel mechanisms essentially emulates the reciprocal interaction within each of these mechanisms. Mathematically, this means that the constants  $a$  and  $b$  in Equations 2 and 3 are not arbitrary, but rather are related by

$$a^2 + b^2 = \text{const.}$$

Equivalently, on taking this constant for unity, one can represent saturation by the angle  $\gamma$ , defined by

$$a = \sin \gamma, \quad b = \cos \gamma. \quad (4)$$

Such a second-order reciprocal interaction manifests itself in the fact that the two primary color circles, the chromatic one ( $X_1X_2$ ) and the brightness one ( $X_3X_4$ ), unite within the structure of the single four-dimensional sphere:

$$X_1 = \cos \alpha \sin \gamma, \quad X_2 = \sin \alpha \sin \gamma, \quad X_3 = \cos \beta \cos \gamma, \quad X_4 = \sin \beta \cos \gamma, \quad (5)$$

which is equivalent to Equation 1.

It is easy to see that if one fixes the level of brightness ( $\beta$ ) and allows the color hue ( $\alpha$ ) to vary freely (i.e., if one considers a set of equally bright colors), then

$$\min\{X_3, X_4\} = c \max\{X_3, X_4\},$$

where  $c$  is a constant determined by the constant value of  $\beta$ . On denoting

$$\bar{X}_3 = \sqrt{X_3^2 + X_4^2} = \sqrt{1 + c^2} \max\{X_3, X_4\} \quad (6)$$

one readily derives from Equation 1 or from Equation 5 that the space of equally bright colors is described by the relationships

$$X_1 = \cos \alpha \sin \gamma, \quad X_2 = \sin \alpha \sin \gamma, \quad \bar{X}_3 = \cos \gamma, \quad X_1^2 + X_2^2 + \bar{X}_3^2 = 1. \quad (7)$$

Thus the prediction of the spherical model of color discrimination is that the configuration of equally bright colors is a three-dimensional sphere. The MDS analysis of dissimilarities among colors of equal brightness corroborates this prediction completely (Izmailov, 1980; Shepard & Carroll, 1966). Note that in this reduced model the traditional two dimensionality (hue and saturation) of the equally bright colors is preserved, as the location of color points on the three-dimensional sphere is characterized by two spherical coordinates: the horizontal angle  $\alpha$  representing the colors' hue and the vertical angle  $\gamma$  representing their saturation.

Considering the three Cartesian coordinates of this reduced model, the two color-opponent channels continue to be represented by the two axes  $X_1$  and  $X_2$ , and  $\bar{X}_3$  is simply one of the two brightness channels of the full model,  $X_3$  or  $X_4$ , with the other channel's output varying in a compensatory fashion so that the brightness level remains constant. As  $\bar{X}_3$  is inversely related to  $\gamma$ , the colors with low values of  $\bar{X}_3$  (those closer to the chromatic plane  $X_1X_2$ ) are more saturated. Clearly  $\bar{X}_3$  is also inversely related to  $\sqrt{X_1^2 + X_2^2}$ , the quantity that can be therefore viewed as an alternative measure of saturation. This is essentially the traditional measure

of the saturation of a color: how far this color is from the center of the chromatic circle (corresponding to the "ideal white").

All this agrees with the results of the MDS analysis of experimental data: The white color has the highest value of  $\bar{X}_3$  and the smallest distance from the  $\bar{X}_3$  axis, whereas the opposite is true for the saturated monochromatic lights, red (620–660 nm), green (510–530 nm), and blue (450–470 nm). The less-saturated monochromatic lights, bluish-green (480–500 nm) and yellow (560–580 nm), fall in between, having intermediate values of both  $\bar{X}_3$  and  $\sqrt{X_1^2 + X_2^2}$ . Finally, the MDS computations confirm that the coordinates  $X_1$  and  $X_2$  in the full four-dimensional model are related to  $\bar{X}_3$  in the reduced three-dimensional model in accordance with Equation 6.

Izmailov and Sokolov (1991) also reported the results of the MDS reconstruction of the space of achromatic stimuli, based on estimated pairwise differences between various gray colors (presented in the disk–annulus paradigm). The prediction of the spherical model of color discrimination in this case is straightforward. The achromatic stimuli have a negligible amount of saturation, which means that  $\gamma = 0$  in Equations 5 and a constant hue, which means that  $\alpha = \text{const.}$  in Equations 5. With no loss of generality one can put  $\alpha = 0$  for gray colors. The resulting reduced model is then

$$X_3 = \cos \beta, \quad X_4 = \sin \beta, \quad X_3^2 + X_4^2 = 1. \quad (8)$$

Thus the predicted spatial configuration is a planar circumference, and this is precisely what the MDS analysis results in. The angle  $\beta$  on the plane clearly represents brightness, and the two Cartesian axes represent the dark and the bright channels of the brightness encoding system.<sup>1</sup>

### RECONSTRUCTION OF THE COLOR SPACE FROM VISUAL EVOKED POTENTIAL AMPLITUDES

We turn now to the reconstruction of the human color-discrimination space by means of applying MDS to neurophysiological data. The experimental paradigm that makes this possible consists of recording a neurophysiological response of the visual system to an abrupt replacement of one color by another: The magnitude of this response is interpreted as monotonically related to the neurophysiological difference between the two colors. In particular, the absence of a response indicates

<sup>1</sup>A striking prediction of the spherical model that as yet has not been tested is that the spatial configuration of equal-hue colors (e.g., green colors varying in brightness and saturation) has to be a three-dimensional sphere.

that the two colors are neurophysiologically identical, a logic used by Bongard (1955) to establish color-mixture equations for animals. As an example especially relevant to the present work, in Riggs, Blough, and Schafer (1972) the response to color changes is the electroretinogram of the pigeon's eye, and the amplitude of the *b*-wave is treated as monotonically related to color differences. The matrix of *b*-wave amplitudes thus obtained is analyzed by means of MDS, resulting in the reconstruction of a color space for the pigeon's retina. The geometric characteristics of this space turn out to closely match those of the trichromatic human color space.

The colors used by Riggs et al. (1972) were adjusted by the experimenters to appear equal in brightness, with the intent of interpreting the color differences measured by the *b*-wave as purely chromatic. This procedure, however, is logically flawed, as there is no assurance that the thus-defined equal brightness has the same meaning as equal brightness for a specific neurophysiological system (in this case, the retina) of an altogether different species. To solve the problem of obtaining a neurophysiological measure of purely chromatic color differences, Zimachev, Shekhter, Sokolov, and Izmailov (1986) and Izmailov, Isaychev, Korshunova, and Sokolov (1998) developed a different procedure.

Let  $C_0$  and  $C_1$  denote two colors (the reference color and the comparison color, respectively) with fixed spectral compositions  $S_0$  and  $S_1$ . Let the intensity of the reference color  $C_0$  be fixed at a level  $I_0$ . As the intensity  $I_1$  of the comparison color  $C_1$  varies, the neurophysiological response varies too, forming a V-shaped curve (see Fig. 2.3): It is large if  $I_1$  greatly differs from  $I_0$  in either direction, and it achieves a minimum level at some intensity

$$I_1 = f(S_0, S_1, I_0).$$

When  $S_0 = S_1$  (Fig. 2.3, solid line),  $f(S_0, S_1, I_0)$  coincides with  $I_0$ , the response then being at the background level. When  $S_0 \neq S_1$  (Fig. 2.3, dashed line), the response to the change,

$$(S_0, I_0) \Rightarrow [S_1, f(S_0; S_1; I_0)],$$

should be taken to reflect the irreducible difference between the two colors that is due to the difference in their spectral compositions only. In this way one can obtain a set of stimuli that are equal from the point of view of a specific neurophysiological system in all respects but their chromaticity. The responses of this system to these stimuli then can be used to reconstruct a space of purely chromatic differences. Zimachev et al. (1991) used this technique to reconstruct the space of "equally bright" colors for the frog's retina. This space turned out to be similar to that for human trichromats, except for showing much coarser discrimination: Although spectral colors occupy positions different from each other and from that of the white color, less-saturated colors virtually coincide with the white color.



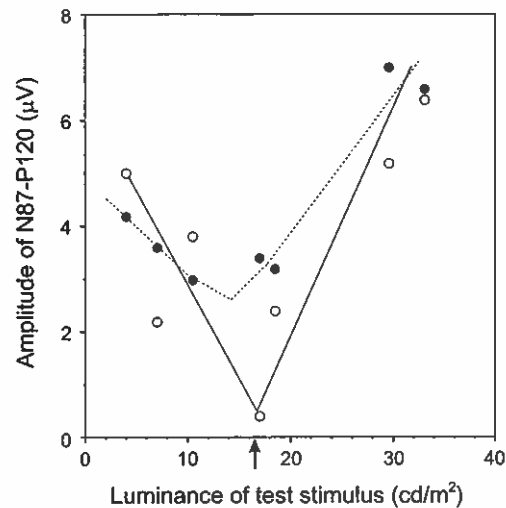


FIG. 2.3. N87-P120 interpeak amplitude of the visual evoked potential (site O1) obtained in response to abrupt color changes (from a reference stimulus to a test one) as a function of the test-stimulus luminance. The luminance of the reference stimulus is indicated by the arrow on the horizontal axis. The open circles and solid line represent a situation in which the two colors have identical spectral distributions (green colors), and the filled circles and dashed line represent changes from a white reference color to a green test one.

The significance of this technique is also due to the fact that the visual system, on both the retinal and the cortical levels, is much more sensitive to brightness differences than it is to chromatic ones: The V-shaped curves just described are very sharply tuned at their minima, that is, even slight deviations from  $I_1 = f(S_0, S_1, I_0)$  cause the retinal or the cortical response to increase dramatically (Izmailov et al., 1998; Riggs & Sternheim, 1969; Zimachev et al., 1986, 1991).

The neurophysiological interpretation of the Cartesian coordinates in the spherical model of color discrimination implies that subjective estimates of color dissimilarities should be reflected in the electrical activity of the human brain. By appropriately choosing the type of the electrical activity and by subjecting it to MDS, one should be able to obtain a color space essentially identical to the one obtained from psychophysical data. In our previous work (Izmailov, 1997; Izmailov & Sokolov, 1991), the validity of this expectation was demonstrated for the discrimination of achromatic lights. Here we present experimental data that demonstrate the identity of the psychophysical and neurophysiological color discrimination spaces for chromatic stimuli.

## Method

Details of the presentation/recording procedure subsequently described can be found in Paulus, Homberg, Cuninghum, Halliday, and Ronde (1984), Zimachev et al. (1986), and Izmailov et al. (1998). Twelve combinations of the basic monitor colors, red, green, and blue (R, G, and B), were used as stimuli in both the psychophysical and the neurophysiological experiments, each stimulus covering the subject's entire visual field. Five colors (red, yellow, green, blue, and white) were made equal in brightness by means of the procedure already described (see Fig. 2.3), involving the minima of the V-shaped curves. As the resulting values of  $I_1 = f(S_0, S_1, I_0)$  turned out to be sufficiently close to the brightness matches obtained by the conventional heterochromatic matching procedure, the latter was used to equate the remaining seven colors to the brightness of the white color. The resulting characteristics of the color stimuli are given in Table 2.1. The participants were normal trichromats who viewed the monitor with no head restraint, but with a fixation point preceding the presentation of stimuli.

In the neurophysiological experiment the presentation consisted of two colors interchanging 50 times:  $C_0 \rightarrow C_1 \rightarrow \dots \rightarrow C_0 \rightarrow C_1$ , with the durations of the colors randomly varying between 800 and 1200 ms to avoid rhythm-related artefacts. In response to each change we recorded occipital ( $O1, O2$ ) and temporal ( $T5, T6$ ) evoked potentials (for 340 ms following the change; the background electroencephalogram was recorded for 60 ms preceding the change). The visual evoked potentials (VEPs) were averaged over the 50 records after artifacts were removed.

TABLE 2.1  
Characteristics of Color Stimuli Used in the Psychophysical and  
Psychophysiological Experiments

Color	Chromatic Coordinates		Luminance ( $cd/m^2$ )	Wavelength (nm)
	x	y		
Red	0.612	0.342	14	610
Red-yellow	0.552	0.403	15	590
Yellow	0.484	0.446	14	580
Yellow-green	0.400	0.506	13	565
Green-yellow	0.306	0.575	14	550
Green	0.259	0.397	13	515
Green-blue	0.227	0.291	12	485
Blue-green	0.204	0.198	11	475
Blue	0.153	0.068	12	470
Blue-red	0.223	0.114	14	450
Red-blue	0.371	0.182	13	
White	0.299	0.295	13	

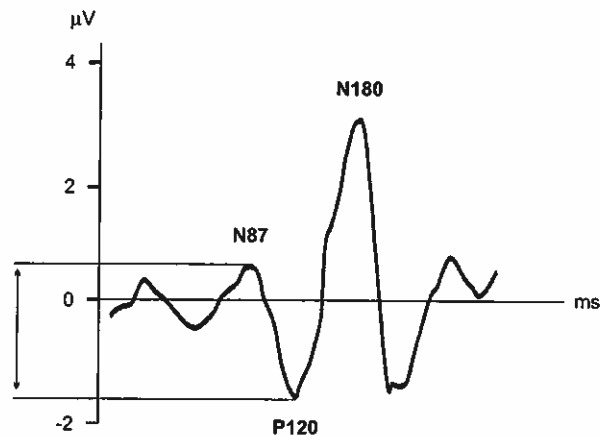


FIG. 2.4. An example of VEP in response to a color substitution.

Three different measures of the averaged VEP magnitude were used (Fig. 2.4): the amplitude of the component N87 relative to the background level, the interpeak difference between N87 and P120, and the interpeak difference between P120 and N180.

The same 12 colors, under the same viewing conditions, were used in the psychophysical experiment, except that a presentation here consisted of a single change  $C_0 \rightarrow C_1$ , two 800-ms colors separated by a 1-s dark interval. Color pairs were randomized, each pair being presented 10 times in total. The participant's task was to numerically estimate the difference between the two colors on a 10-point scale, from 0 (identical colors) to 9 (most different colors).

## Results and Discussion

All the subsequent results are shown for a single individual who participated in both the psychophysical experiment and the neurophysiological one. The results are presented as graphs of the averaged VEPs (Fig. 2.5) and as configurations of points in a color space (Fig. 2.6).

Below we discuss only the VEPs obtained from *O1* and *T5* recording sites, because those for the corresponding occipital (*O2*) and temporal (*T6*) sites are essentially the same. The analysis of the neurophysiological experiment therefore is based on six matrices, each corresponding to one of three measures of VEP (N87, N87-P120, or P120-N180) and one of two recording sites (*O1* or *T5*). Together with the matrix of the numerical estimates of color dissimilarities obtained in the psychophysical experiment, these six matrices were subjected to MDS. In each case the goodness of fit for the MDS solutions was estimated by means of the conventional stress measure and by the coefficients of correlation between the

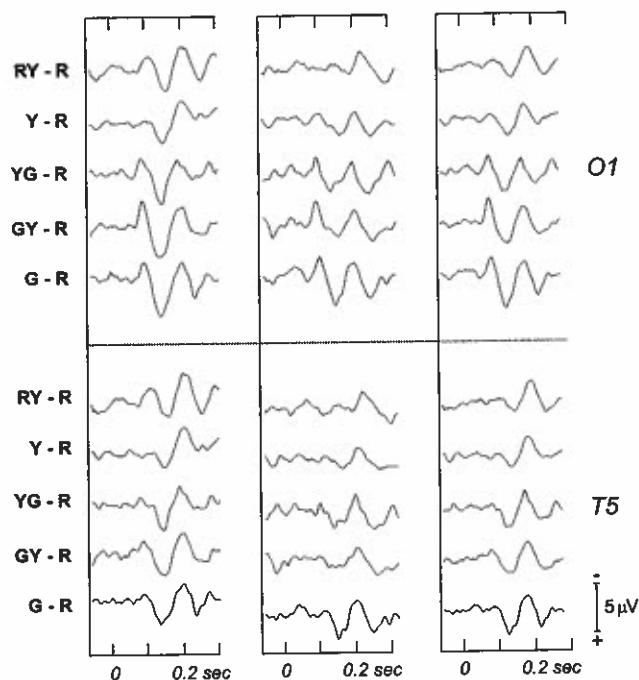


FIG. 2.5. VEPs recorded in response to changes from a test stimulus to a reference stimulus (first column) and vice versa (second column). The third column represents the average of the first two. The letters R, G, and Y stand for red, green, and yellow, respectively; the upper panel represents occipital VEPs (site O1), and the lower panel represents temporal VEPs (site T5).

interpoint distances and the matrix entries (numerical estimates or VEP amplitudes, respectively).

By these criteria a four-dimensional Euclidean space provides a good solution for all matrices. Although a three-dimensional solution was not significantly worse, we used the four-dimensional one to compare the VEP-based and psychophysical color configurations for the following reason. As mentioned in the method section, 5 of the 12 colors used in the experiments were matched in brightness by means of the procedure illustrated in Fig. 2.3, neurophysiologically, whereas the remaining 7 colors were matched in brightness to the white color psychophysically by means of the heterochromatic matching procedure. Although the two matching procedures do produce similar luminance values, these values are not identical. Consequently, the colors matched in brightness psychophysically were not precisely matched in brightness neurophysiologically, and vice versa. At the same time, the same set of 12 colors was used in both our experiments. As already explained, equally

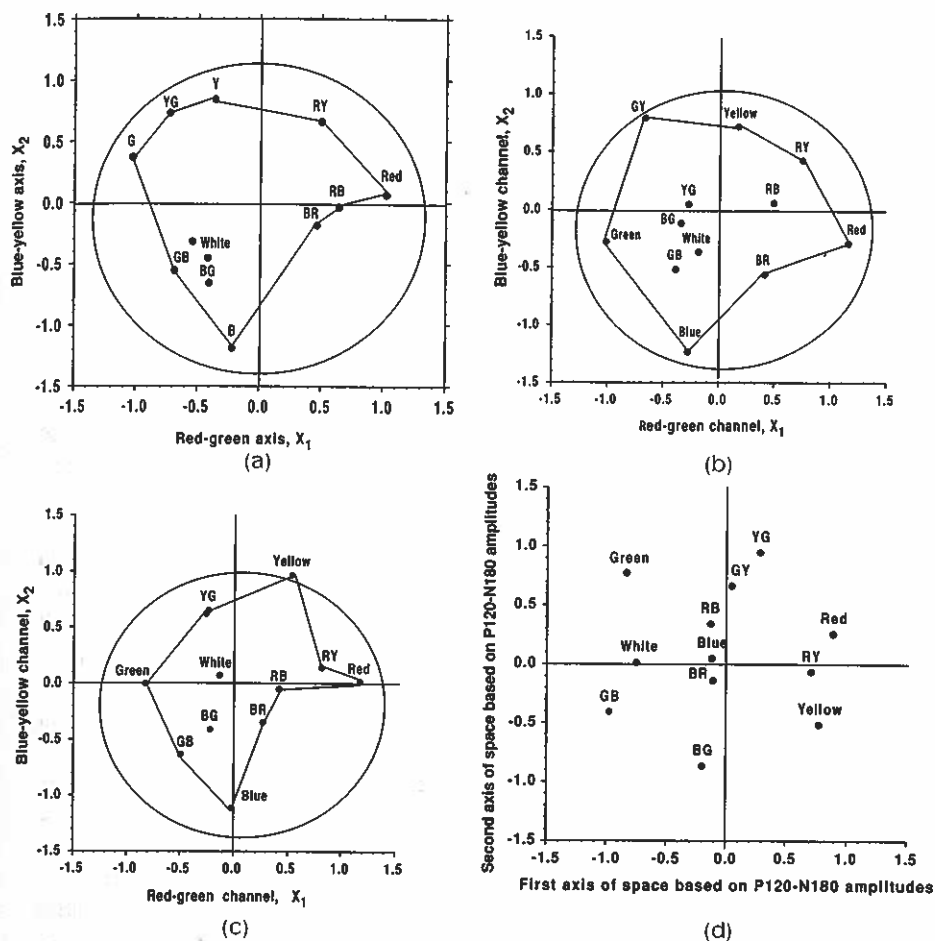


FIG. 2.6. Projections of color points on the chromatic plane ( $X_1, X_2$ ) of the four-dimensional color sphere constructed on the basis of (a) numerical estimates of color dissimilarities and three measures of occipital VEPs (site O1): (b) N87 amplitude, (c) N87-P120 interpeak difference, and (d) P120-N180 interpeak difference.

bright colors lie on a three-dimensional sphere. If the brightness equality across the colors is only approximate, however, one should expect, in accordance with the spherical model of color discrimination, that the colors lie on the surface of a four-dimensional sphere but sufficiently close to one of its three-dimensional cross sections. This prediction agrees with the observed results.

The sphericity of the color configurations in the four-dimensional Euclidean solutions provided by MDS was tested by means of an iterative computational

TABLE 2.2  
Two Goodness-of-Fit Indices

Index	Numerical Dissimilarities	MDS Based on					
		N87		N87-P120		P120-N180	
		O1	T5	O1	T5	O1	T5
Pearson correlation	0.98	0.87	0.85	0.89	0.87	0.89	0.86
Coefficient of variation (%)	12	16	19	15	18	22	28

Note. The correlation between interpoint distances and initial matrix entries characterizes the quality of the four-dimensional MDS solution, whereas the coefficient of variation (sphere thickness) characterizes the sphericity of the configuration of color points.

procedure that searched for the center of the sphere, that is, the point in the space whose distances from all 12 colors had the smallest possible variance. The eventually achieved variation coefficient (the standard deviation of the radii as a proportion of their mean) serves as a measure of sphericity: The smaller this coefficient (the thickness of the sphere), the better the sphericity. The results are given in Table 2.2. Plainly, the overall quality of the four-dimensional Euclidean solution, as estimated by the Pearson correlation coefficients, is almost equally good in all cases. Note that the nonmetric MDS procedure used in our computations requires a monotonic but not necessarily linear relationship between interpoint distances and matrix entries. As a result, the Pearson correlation is only a crude goodness-of-fit measure.

The degree of sphericity, however, as measured by the coefficient of variation clearly differs for different matrices. It is best for the numerical estimates of color dissimilarities, with only 12% thickness of the sphere. For the occipital N87 and N87-P120 amplitudes the sphericity is only slightly worse (16% and 15%, respectively). The sphericity deteriorates for the temporal N87 and N87-P120 amplitudes of VEP, and for the P120-N180 amplitudes, both occipital and temporal, the coefficient of variation is so high that with a high degree of confidence here one can reject a spherical model as a reasonable approximation.

Figure 2.6 presents the projections of the color points on the chromatic plane  $X_1X_2$  computed from the MDS solutions for the numerical estimates of color dissimilarities [Fig. 2.6(a)] and for the occipital N87, N87-P120, and P120-N180 amplitudes of VEP [Figs. 2.6(b), 2.6(c), and 2.6(d), respectively]. The configuration obtained for the numerical estimates is essentially a version of the one shown in Fig. 2.1(a). The colors form a classical Newtonian contour, from the red through orange to yellow and so on along the spectrum, until the contour is closed by the purple colors (blue-red and red-blue). The white color occupies a position near the origin of the  $X_1X_2$  plane. (The blue-green color falls closer to the white than the other colors because of the well-known bleaching of the blue-green mixtures on all conventional monitor screens.)

The most important observation, however, is that essentially the same configuration of color points is obtained from the MDS analyses of the N87 and the N87-P120 amplitudes of VEP. The differences between the three configurations shown in panels (a), (b), and (c) of Fig. 2.6 are local and can be attributed to measurement errors as well as to real but second-order processing differences imposed on one and the same overall picture.

By contrast, the configuration of points obtained from the MDS analysis of the P120-N180 amplitudes of VEP is essentially random: Observe that the white color falls farther away from the origin than the more saturated blue, that the yellow has almost the same horizontal coordinate (which is supposed to represent the red-green opponent system) as the red, and that the order of the colors on the vertical axis is opposite to that consistent with its interpretation (as representing the blue-yellow opponent system). This justifies our rejection of the spherical model for this VEP component on the basis of the high sphere thickness and leads one to the conclusion that the late components of the cortical VEP may have little to do with color processing.

## CONCLUSION

Although animal color vision has been extensively studied at the level of light receptors and individual neurons (Gouras & Padmos, 1974; Padmos & Van Norren, 1975; Zeki, 1980; Zrenner, 1983), analogous studies in humans are scarce because of obvious procedural limitations. The recording of the mass electrical activity of the brain therefore remains an indispensable tool in linking neurophysiological and psychophysical aspects of color vision. It seems, however, that the mass electrical activity, such as cortical or retinal evoked potentials, is truly informative only if it is recorded in response to an abrupt change of one stimulus to another, rather than, as is done traditionally, to a presentation of an individual stimulus (Ivanicsky & Strelecs, 1976; Regan, 1970; Shipley, Jones, & Fry, 1965; White, Kataoka, & Martin, 1977). The present results show that early components of the VEPs generated in the human striate cortex (*O1* and *O2* sites) in response to color changes contain essentially the same information about subjective differences among colors as one can extract from conscious estimates of these differences. In both cases the information extracted (by means of MDS) is in good compliance with the spherical model of color discrimination.

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