Errata:

1) On page 200, the coefficient on B^1/3 for the j coordinate in Eq. 5.2 should be -9.7, rather than the +9.7 that is published.

2) On page 203, Eq. 5.4, the upper expression for L* should be L* = 116(Y/Yn)^1/3-16. The exponent 1/3 is omitted in the published text. In addition, the leading factor in the expression for b* should be 200 rather than 500.

3) In the expression for "deltaH*_94" just above Eq. 5.8, each term inside the radical should be squared.

5

Color Appearance and Color Difference Specification

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CHAPTER CONTENTS

The Science of Color
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5.1 INTRODUCTION

The physical properties of color stimuli may be specified using spectral measurements or tristimulus coordinates. Such specification, however, provides little intuition about how the stimuli will appear. For applications such as color selection we would like to specify color using appearance terms and have an automatic method for computing the corresponding tristimulus coordinates. To do so we need to understand the relation between the physical description of a color stimulus (e.g. its tristimulus coordinates) and a quantitative description of its color appearance.

A second topic of practical importance is to specify the magnitude of differences between colored stimuli. Here we need to understand the relation between changes in the physical description of a color stimulus and corresponding changes in appearance. In specifying color reproduction tolerances, we are likely to be concerned with small color differences: how different must the tristimulus coordinates of two stimuli be before the color difference between them is just barely noticeable? For color coding, on the other hand, we are more likely to be concerned with whether two colors are sufficiently different to be easily discriminable. For example, if we are designing traffic signals we would like to be sure that the red and green lights are easy to tell apart.

There are a number of systematized methods available both for specifying color appearance and for specifying color difference. Unfortunately, no perfect system exists for either purpose. To use the systems successfully, it is necessary to have a firm grasp of the principles underlying their design. The purpose of this chapter is to provide an introduction to color specification systems and some guidance as to their use. A detailed survey of such systems is not attempted here, but a number of excellent reviews are available (Judd and Wyszecki, 1975; Robertson, 1984; Billmeyer, 1987; Hunt, 1987b; Derefeldt, 1991; Fairchild, 1998). This chapter builds on the material introduced in Chapters 3 and 4. Chapter 3 introduces the color matching experiment and describes how tristimulus coordinates may be used to represent the spectral properties of light. Chapter 4 discusses the phenomenology of color appearance and describes the psychological attributes of hue, saturation/chroma, and brightness/lightness.

The chapter begins with a discussion of color order systems. A color order system is a type of color appearance system – that is, a type of system for specifying color appearance. In a color order system, the color appearance of a carefully selected set of color samples is specified. The samples are arranged to make it easy to find a desired color and to allow visual interpolation between samples. To help fix ideas, a detailed review of the popular Munsell color order system is provided, followed by a brief description of a few other systems. Next comes an overview of color difference systems. The overview begins with a concrete example, the CIELAB uniform color space, which is useful for specifying small color differences. Following the example, a few other systems are briefly described. The chapter closes with discussion of a number of issues and topics.

5.2 COLOR ORDER SYSTEMS

5.2.1 EXAMPLE: MUNSELL COLOR ORDER SYSTEM

5.2.1.1 Problem – specifying the appearance of surfaces

The Munsell color order system was originally conceived by A.H. Munsell in 1905 (Munsell, 1992). His goal was to provide a system for specifying colors and for teaching students about the perceptual attributes of color. He devised a symbolic notation for color appearance; this is referred to as Munsell notation. Munsell's system was operationalized as a collection of color samples, so that it was possible to understand visually the relation between Munsell color names and the corresponding color percepts. The Munsell system has been modified several times to improve the correspondence between the actual samples and the underlying perceptual organization (Nickerson, 1940; Berns and Billmeyer, 1985).

Current collections of samples (see http://munsell.com/) implementing the Munsell system are based on the results of an extensive study by an Optical Society of America committee in the 1930s and 40s (Newhall, 1940; Newhall *et al.*, 1943). This committee conducted scaling experiments on samples from an early edition of the Munsell Book of Color. It also made physical measurements of the samples. Based on these data, it generated extensive tables relating Munsell notations to the tristimulus coordinates (under standard conditions of illumination) that a sample of that notation should have. This tabulation now defines the Munsell system, and is sometimes referred to as Munsell renotation.

5.2.1.2 Perceptual ideas

The basic idea underlying the Munsell system is that color appearance may be described in terms of three attributes: hue, chroma, and lightness (see Chapter 4). The system therefore consists of scales for each of these attributes.

Munsell **hue** is a circular scale based on 10 major hues, Red (R), Yellow–Red (YR), Yellow (Y), Green–Yellow (GY), Green (G), Blue–Green (BG), Blue (B), Purple–Blue (PB), Purple (P), and Red–Purple (RP). In addition, the 10 major hues are subdivided further into a scale that ranges from 1 to 10, with 5 denoting the major hue itself. A digit–letter notation is typically used to specify Munsell hue, so that 2.5R would refer to step 2.5 in the major hue category red. Equal steps on the Munsell hue scale are designed to represent equal changes in perceived hue. Thus the 10 subdivisions of the 10 major hues form a 100 point scale for hue.

Munsell **chroma** is specified on a numerical scale starting at 0 and extending out to the maximum possible chroma for each hue. A chroma of zero indicates a black, gray, or white. Increasing chroma numbers indicate progressively more pure color percepts. Samples that differ in Munsell hue but that have the same chroma should be judged to differ equally from an achromatic sample of the same lightness. Equal steps on the chroma scale are meant to represent equal changes in perceived chroma.

The Munsell scale for **lightness** is called value. Munsell value is specified on a numerical scale that ranges from 0 for colors judged to have the same lightness as black to 10 for colors judged to have the same lightness as white. Samples that differ in Munsell hue or chroma but that have the same value should be judged to have the same lightness. Equal steps on the value scale are designed to represent equal changes in perceived lightness.

The notational form used to express Munsell colors begins with the hue, followed by the value and chroma numbers. These latter two are separated by a slash. Thus the notation 2.5R 8/4 refers to a sample with hue 2.5R, value 8, and chroma 4. The letter N is used to denote neutral samples and the chroma value is omitted. Thus N 8/ is used to indicate a neutral sample of value 8 and 0 chroma. In the Munsell scheme, any stimulus (provided it is seen in surface mode) has a color appearance that may be described by the appropriate Munsell notation. See Chapter 4 for a discussion of modes of appearance.

5.2.1.3 Geometric representation

If we hold the attribute of hue constant, it is natural to represent Munsell value and chroma using rectilinear coordinates. A rectilinear representation makes sense for these two attributes because each has a well-defined origin (black for value, neutral for chroma) and because numerical differences on each scale are related monotonically to perceived color difference.

The situation is not so simple for Munsell hue. First, there is no natural origin for hue. Second, there is no linear scale for hue such that numerical differences on the hue scale are monotonically related to perceived differences. It is possible, however, to represent hue geometrically using a polar coordinate system. It turns out that when hue is arranged in a circular fashion, distances between points provide a reasonable approximation to their perceptual differences (see Chapter 4).

The rectilinear representation for chroma and value may be combined with the circular representation for hue to provide a cylindrical coordinate system for the Munsell system. In cylindrical coordinates, the angular coordinate represents hue, the linear coordinate represents value, and the radial coordinate represents chroma. Any stimulus seen in surface mode can thus be thought of as a point in a three-dimensional Munsell space. The geometry of the Munsell system is illustrated in Figure 5.1.

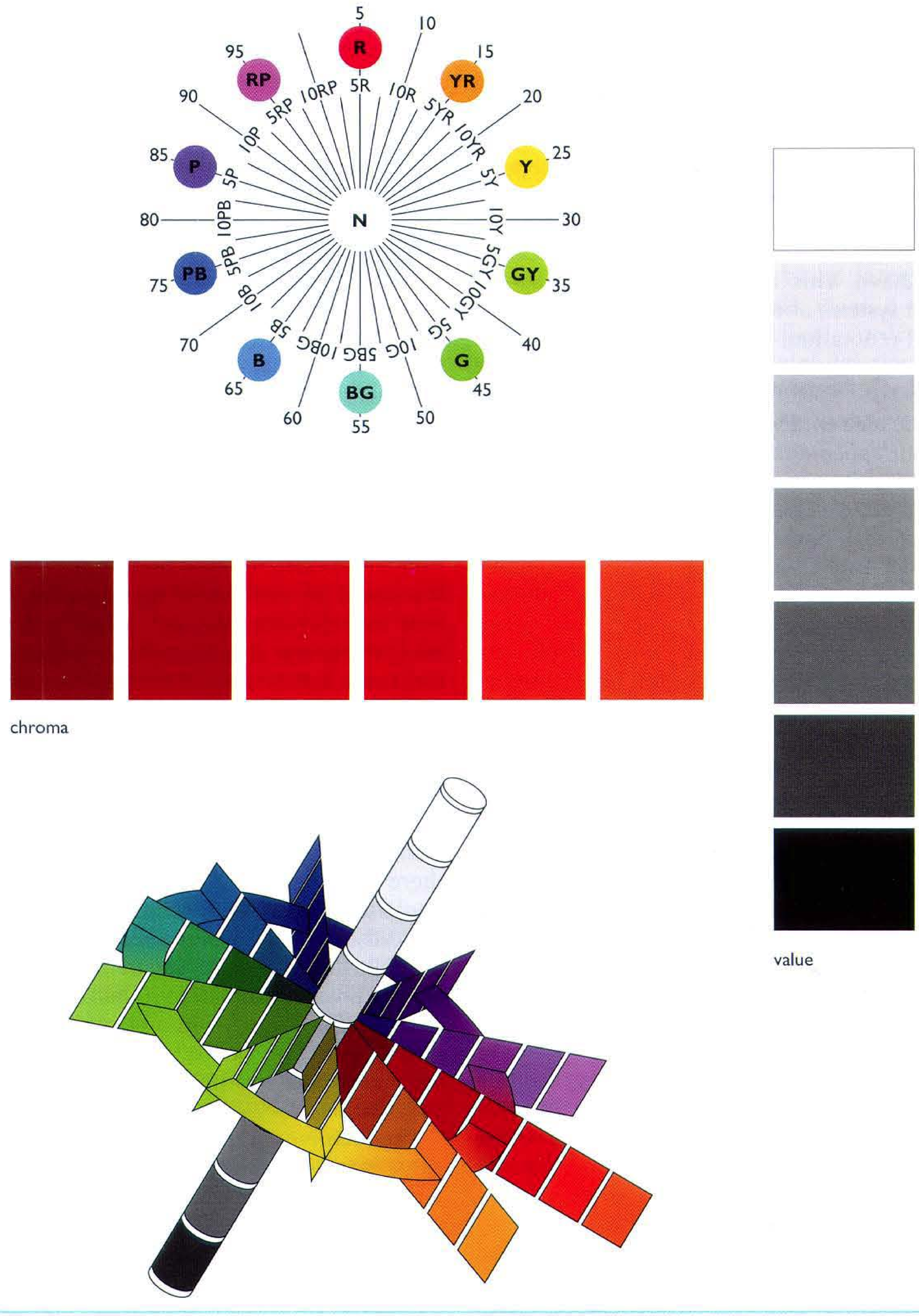


Figure 5.1 The Munsell color order system. The Munsell hue circle (upper left) is a series of neutral colors that vary in value only (vertical series on right), and a series that varies in chroma at constant hue and value (middle left). As shown at the lower left, the Munsell system may be organized cylindrically, with an angular coordinate representing hue, a linear coordinate representing value, and a radial coordinate representing chroma. (Courtesy of Munsell Color Services, a division of GretagMacbeth.)

5.2.1.4 Relating Munsell notations to stimuli

Note that the conceptual system described above describes perceptual variables and is independent of any specification of which stimuli elicit particular perceptions (e.g. Figure 5.1). Another way to say this is that, in principle, one can imagine the appearance of any Munsell specification without ever having seen a set of Munsell samples. Thus we can regard the Munsell system as a theory that describes the phenomenology of color perception. No direct experiments justified this theory; it was derived primarily from Munsell's own introspection.

The Munsell system would not have much practical value if it were only an abstract theory of perception. The usefulness of the system arises because there exist a set of samples that exemplify the system. The original implementation of the Munsell scheme was created by A.H. Munsell in conjunction with an artist who carefully painted samples to match Munsell's conception. This led to the production of the Munsell Color Atlas in 1915 (Munsell, 1915). Subsequent work (Munsell *et al.*, 1933; Godlove, 1933) focused on refining the value scale for neutral colors. Thresholds for detecting just-noticeable-differences (JNDs) were measured over a range of stimuli that appeared from black to white, and a scale of equal JND steps was generated from the data. This scale was validated using a variety of other scaling procedures. The value scale thus created formed the backbone of the 1929 *Munsell Book of Color* (Berns and Billmeyer, 1985).

The exact judgments used to determine the samples corresponding to other Munsell notations are not well documented. Basically, however, the following scheme was used (Berns and Billmeyer, 1985). First, judgments were made to equate the lightness of non-neutral colors to those of neutral colors. The result was an assignment of values to a large number of samples. Given a collection of samples of equal value, observers then scaled these according to their hues and chromas. There were two goals of the scalings. The first was to equate the numbers assigned for one attribute across variations in the other, so that within a set of samples with equal value, lines of constant hue and constant chroma were defined. Second, the differences between lines of constant hue and chroma were scaled and the numerical scales adjusted so that equal steps on each scale corresponded to equal perceptual differences. Finally, judgments across colors of differing value were made, so as to equate the hue and chroma scales across variations in value.

The current specification of the relation between Munsell notations and physical samples is based on experiments performed on the 1929 samples by a committee of the Optical Society of America (Newhall, 1940; Newhall *et al.*, 1943). Observers performed two types of tasks in these experiments. In one, they judged whether the 1929 samples in fact satisfied the requirements of the Munsell perceptual scheme. In one experiment, for example, observers viewed a series of samples that had the same nominal hue and value but that varied in chroma. They then indicated whether the samples in fact appeared to have the same hue and scaled the direction and magnitude of any deviations. This type of judgment was used to identify adjustments required to achieve better lines of constant hue, chroma, and value. In a second type of task, observers judged differences between samples from the 1929 book. For example, observers were shown two pairs of samples differing in hue but with the same value and chroma. They were then asked to judge the ratio of the differences between the two pairs. This type of judgment was used to adjust the spacing of the samples in the 1929 judgment to more closely approximate the even perceptual spacing that is the goal of the Munsell scheme.

In addition to scaling experiments on the 1929 samples, the committee also made physical measurements of the samples. By analyzing the relation between perceptual judgments and physical tristimulus coordinates, the committee generated extensive tables relating Munsell notations to the tristimulus coordinates that a sample of that notation should have (under standard conditions of illumination). The actual analysis was performed graphically by plotting the measurements on large pieces of graph paper and fitting smooth curves by hand, so that no analytic expression for the relation between Munsell notation and tristimulus coordinates exists. The tabulation now defines the primary implementation of the Munsell system, and is sometimes referred to as Munsell renotation.

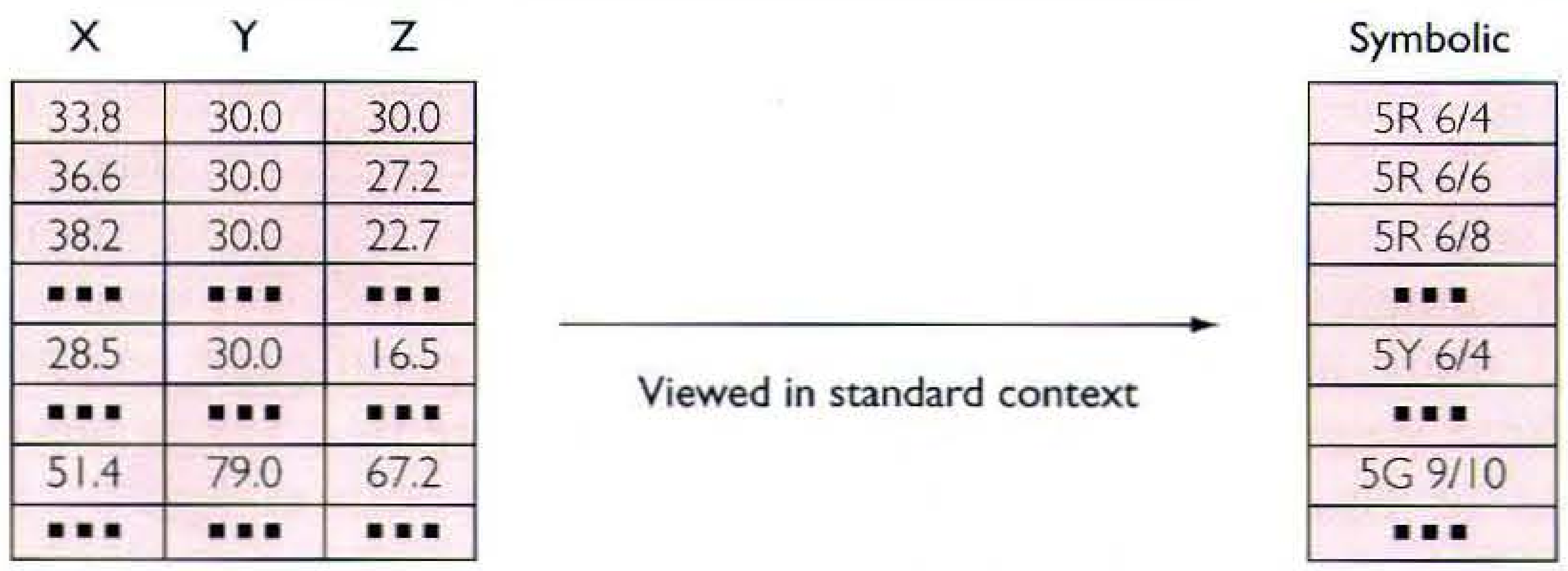
Current implementations of the Munsell system conform closely to the renotation aim points.

5.2.1.5 Discussion

The Munsell color order system may be thought of as consisting of two parts. The first is an abstract perceptual scheme for specifying colors. The second is a large lookup table that defines an instantiation of the Munsell scheme (see Figure 5.2). One side of the table contains tristimulus coordinates of samples. The other side of the table contains the symbolic description corresponding to each sample when it is viewed under standard conditions. Typically these conditions are isolated viewing against a uniform nonselective (gray) background under a specified illuminant. The exact details of the standard viewing conditions vary across color order systems and even for different implementations of the same color order system. The mapping between tristimulus coordinates and symbolic descriptions is defined only for the standard conditions.

As emphasized by McCamy (McCamy, 1985), it is useful to maintain the distinction between a color order system's perceptual scheme and implementations of this scheme. In evaluating a color order system, we can ask two types of questions. First, does the perceptual system on which the system is built provide a useful characterization of color appearance? Second, does a particular instantiation of the system conform to the underlying perceptual ideas? Note, for example, that the mapping between names and tristimulus values is valid only for one set of viewing conditions. These are the conditions under which the scaling experiments that defined the table were performed. For the Munsell system, these were viewing under CIE Standard Illuminant C (an approximation to daylight), with the samples placed against a nonselective background with a reflectance of approximately 18% (Munsell sample N 5/). The mapping is not necessarily valid for other viewing conditions, but that does not mean that the Munsell perceptual scheme could not be applied generally. Rather, it would take another set of scaling experiments or a model of the effect of context on color appearance to provide the appropriate implementation.

The lookup table view of the implementation of color order systems is simplistic, as it neglects the geometric structure that may be imposed on the arrangement of the symbolic names. It does capture the fact that the mapping between tristimulus coordinates and symbolic names is complex. Indeed, an analytic description of this mapping for implementations of the Munsell system has been elusive. Practical translation between tristimulus coordinates and Munsell names is accomplished by lookup table search and interpolation, sometimes with the aid of neural networks (Simon and Frost, 1987; Smith, 1990a; Burns *et al.*, 1990; Usai *et al.*, 1992; Tominaga, 1993). The difficulty with these methods is that they require large databases specifying either the table entries or summaries thereof. Wyszecki and Stiles (1982) provide tabulations of tristimulus coordinates and corresponding symbolic descriptions for the Munsell and other color order systems. A program for performing the conversion is available free of charge from the GretagMacbeth Corporation (http://munsell.com/).



X	Y	Z
33.8	30.0	30.0
36.6	30.0	27.2
38.2	30.0	22.7
▪▪▪	▪▪▪	▪▪▪
28.5	30.0	16.5
▪▪▪	▪▪▪	▪▪▪
51.4	79.0	67.2
▪▪▪	▪▪▪	▪▪▪

Symbolic
5R 6/4
5R 6/6
5R 6/8
▪▪▪
5Y 6/4
▪▪▪
5G 9/10
▪▪▪

Figure 5.2 Lookup table view of a color order system implementation. One side of the table contains tristimulus coordinates of samples. The other side of the table contains the symbolic description corresponding to each sample when it is viewed under standard conditions. Typically these conditions are isolated viewing against a uniform non-selective (gray) background under a specified illuminant.

The Munsell system is useful for several purposes. First, it allows us to specify colors in appearance terms. With a little training, observers can apparently become proficient at describing colors using Munsell terms (Helson, 1938; Whitfield *et al.*, 1988) so that the Munsell system provides a language for talking about color appearance. In this capacity, the system has been used successfully in scaling experiments that studied the effect of context on color appearance (Helson, 1938; Helson and Jeffers, 1940).

More important, perhaps, is the fact that there exist implementations of the Munsell notational system. Even if a user is unable to name the exact Munsell term for a desired color, he or she can look through the Munsell book of color until a close approximation to the desired color is found. Because the samples are arranged in an orderly way and are evenly spaced, it is possible to interpolate visually between the sample points to specify color more precisely than the sample spacing (Billmeyer, 1988). Once the desired Munsell notation is known, the tables defining the Munsell system in terms of tristimulus coordinates may be used to find a physical specification for the desired color.

Inverse mapping is also possible. A test sample can be compared to the collection of Munsell samples under the standard viewing conditions. It is then possible to interpolate between the near matches and assign a Munsell name to the test sample.

Because of the manner in which it was developed, the Munsell system also provides a metric for the apparent differences between colors. For example, the perceptual difference corresponding to one step of Munsell value should be the same, independent of the hue or chroma of the sample. Note that steps on the three Munsell appearance scales are of different magnitudes. A step of 1 on the value scale is designed to be perceptually equivalent to a step of 2 on the chroma scale and a step of 3 on the hue scale (at chroma 5). Because hue is specified in polar coordinates, the perceptual magnitude of a single hue step varies with chroma.

There are things that the Munsell system does not provide. First, it does not provide any means to take viewing context into account. The same Munsell paper seen in non-standard viewing contexts may appear quite different from what one would expect from its name. If we consider the original Munsell system, based on physical samples, the color constancy of the human visual system will make the specification somewhat robust in the face of changing illumination. Color constancy is not perfect, however, so Munsell notation must be treated carefully in applications where the illuminant is not standard. If we consider Munsell renotation, an additional difficulty arises. Renotation relates tristimulus coordinates of the samples to the Munsell notation. To take changes in illumination into account, it is necessary to calculate how the tristimulus coordinates of an actual sample would change with the illuminant. Some approximations to this calculation are possible (Brainard, 1995). This issue is discussed further in the section on metamerism below.

Second, the Munsell system does not provide a metric for small color differences. Although the Munsell renotation is designed so that equal steps correspond to color differences judged equal, it is important to remember that the color differences judged were well above threshold. For small color differences, one is concerned with visual thresholds, and there is no obvious relation between threshold data and the suprathreshold judgments on which the Munsell system is based (MacAdam, 1974; Robertson, 1977). In addition, it is useful to bear in mind that the Munsell system was based on scaling differences in one of the three color attributes while the others were held fixed. Thus any effects that intrude when all three attributes are covaried are unlikely to be accurately described by the Munsell system.

5.2.1.6 Relation to tristimulus coordinates

The Munsell system may be used to illustrate some of the perceptual effects discussed in Chapter 4. Figure 5.3 shows lines of constant Munsell hue plotted in the CIE 1931 chromaticity diagram. The left panel of the figure shows the plot for Munsell value 2, while the right panel shows the plot for Munsell value 8. Note that in each panel the constant hue lines curve, illustrating the Abney hue shift. Also note that the locations of the lines for particular hues shift considerably between the two panels. The fact that the lines for different value do not superimpose illustrates the Bezold–Brüke

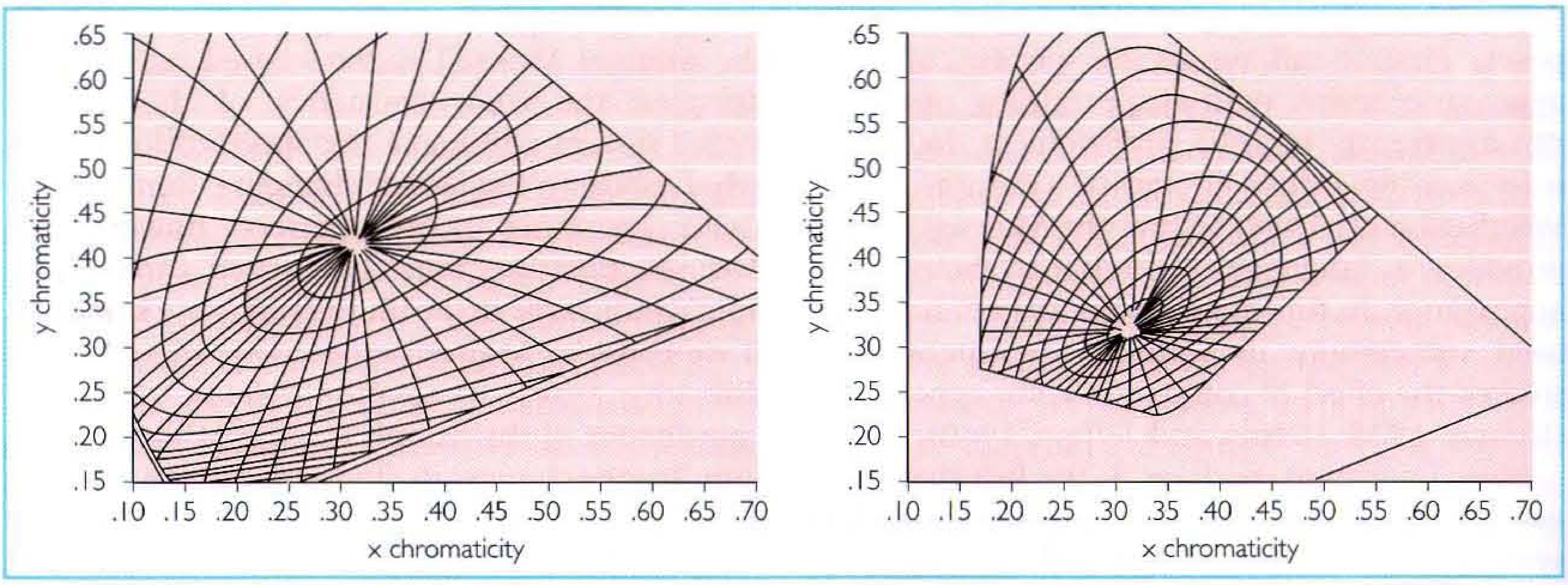


Figure 5.3 **(Left) Lines of constant Munsell hue for Munsell value 2, plotted in the CIE 1931 chromaticity diagram. (Right) Lines of constant Munsell hue for Munsell value 8, plotted in the CIE 1931 chromaticity diagram. (From Wyszecki and Stiles, 1982. Copyright © 1982 John Wiley & Sons, Inc., reproduced by permission.)**

hue shift. Chapter 4 discusses the Abney and Bezold–Brüke shifts in more detail.

The fact that the constant hue lines curve and are not invariant with changes in value illustrates the basic difficulty in specifying color appearance. Simple models of visual processing do not easily predict the shape of the constant hue lines. The search for models that do is currently an area of active research (see section on color appearance models below).

5.2.2 OTHER COLOR ORDER SYSTEMS

The Munsell color order system is not the only color order system. Other color order systems include the Swedish Natural Color System (NCS), the Optical Society of America Uniform Color Scale (OSA/UCS), the Deutches Institut fur Normung (DIN) system, and the Coloroid system. From the discussion above, one can see that there are two primary ways a system could differ from the Munsell system. First, the perceptual principles on which a system is based could differ. Second, the implementation of the system could differ. For example, a system based on the same perceptual principles as the Munsell system but with samples defined for different viewing conditions might be considered a different system. In practice, it is sometimes difficult to decide whether the perceptual principles of two systems differ because the only way to judge what the words mean is to compare the implementations.

Given this general point, it would be possible to compare the details of a large number of systems. Such detailed comparisons are available elsewhere (Billmeyer and Bencuya, 1987; Derefeldt, 1991). It is of interest, however, to discuss some particular color order systems briefly, both to familiarize the reader with them and to illustrate how a system might be built on principles other than those that underlie the Munsell system. Three systems will be discussed: the Swedish NCS, the OSA/UCS, and the DIN color system. None of these systems denies the role of perceptual dimensions related to hue, saturation, and lightness in our perception of color. The first two differ from the Munsell system primarily in that the judgments used to define the system are not direct scalings of such qualities.

5.2.2.1 Swedish Natural Colour System (NCS)

The fundamental scalings underlying the Munsell color order system are judgments of hue, chroma, and value. These are not the only judgments upon which a color order system can be based. Indeed, the NCS is based on a different set of scalings. In the NCS, the appearance of a color is specified by its resemblance to six elementary colors: red, green, blue, yellow, black, and white. This system was developed from opponent process notions (see Chapter 4), in that it is based on the tenet that in judging the color appearance of stimuli, we have access to the outputs of three independent mechanisms: a red–green mechanism, a blue–yellow mechanism, and a white–black mechanism. (The white–black mechanism is sometimes referred to as the luminance mechanism.) If one accepts this tenet, then judging color in terms related to these mechanisms (by asking subjects about resemblances) is a natural choice. Abramov and Gordon (1994) review basic research on this type of judgment. Samples that implement the NCS system exist as the NCS Colour Atlas, and tristimulus specifications for the NCS notations are available (Swedish Standards Institution, 1982; 1983; 1989; http://www.ncscolour.com/). The detailed description that follows is based primarily on Derefeldt's (1991) review.

Although the subject is asked to judge six resemblances in the scalings for the NCS system, there are some constraints on the judgments they are allowed to make. The first restriction is that no color may be judged as resembling both red and green, and no color may be judged as resembling both blue and yellow. Thus a stimulus may be judged to resemble at most two of red, green, blue, and yellow. The NCS hue is defined in terms of the relative resemblances of the stimulus to these four unique hues. (See Chapter 4 for more on unique hues.) The notation used to specify NCS hue is first a letter specifying one unique hue, then a percentage, and then a second letter specifying a second unique hue. Thus R20B indicates a hue where the ratio of the resemblances to red and green are 80 to 20. The sum of the judged resemblances to the four basic chromatic colors (red, green, blue, and yellow) is referred to in the NCS system as chromaticness. The second restriction is that the sum of chromaticness and the resemblance judgments to black and white must be 100. Because of these restrictions, the six NCS resemblances may be specified using only three numbers. These are the two non-zero hue resemblances and the blackness. Because the hue notation is normalized, however, the overall NCS notation for colors is a number for blackness, a number for chromaticness, and an NCS hue specification. For example, 3060 R20B would represent a color whose individual resemblances were 10 for whiteness, 30 for blackness, 48 for redness, 12 for blueness, and zero each for greenness and yellowness.

Although the basic scaling judgments underlying the NCS are six resemblances, the final specification thus ends up in terms of blackness, chromaticness, and hue. These are conceptual relatives of Munsell lightness (inverted), chroma, and hue. Like the Munsell system, the NCS system may be displayed geometrically. The standard NCS geometry within a particular hue is diagrammed triangularly, as shown on the left of Figure 5.4. Vertical lines represent constant chromaticness. Diagonal lines represent loci of constant blackness. The arrangement of the NCS hue circle is also shown in Figure 5.4. Because of the fundamental role played by red, blue, green, and yellow, these four hues are placed equally around the circle. Other stimuli are then placed proportionately according to their relative resemblances to these four cardinal colors.

Although both the Munsell and NCS systems describe color appearance in terms of similar attributes, it is not clear that the two systems represent the same underlying perceptual dimensions. Indeed, direct comparisons suggest that Munsell and NCS hue are quite different from one another (Billmeyer and Bencuya, 1987; Smith *et al.*, 1990b; see Derefeldt, 1991 for an extended bibliography on this topic). Because the systems differ, one can also ask whether one is more easily learned than the other. It has been claimed that the NCS system is superior in this regard (Derefeldt, 1991), but this remains controversial (Whitfield *et al.*, 1988).

5.2.2.2 OSA Uniform Color Scale (OSA/UCS)

The OSA Uniform Color Scale was designed to provide a specification of stimuli whose appearance is equally spaced perceptually. Its design shares much in common with other color order systems and we describe it here rather than with other uniform color spaces. The goal of the OSA committee that designed the system was to produce a set of samples such that the perceptual spacing between neighboring samples was equal, whether the samples differed in hue, saturation, lightness, or any combination of the three. Thus the fundamental scaling judgments underlying the OSA/UCS are perceptual difference judgments. MacAdam (1974) provides the final report of the OSA committee and describes the history of the creation of the OSA/UCS system.

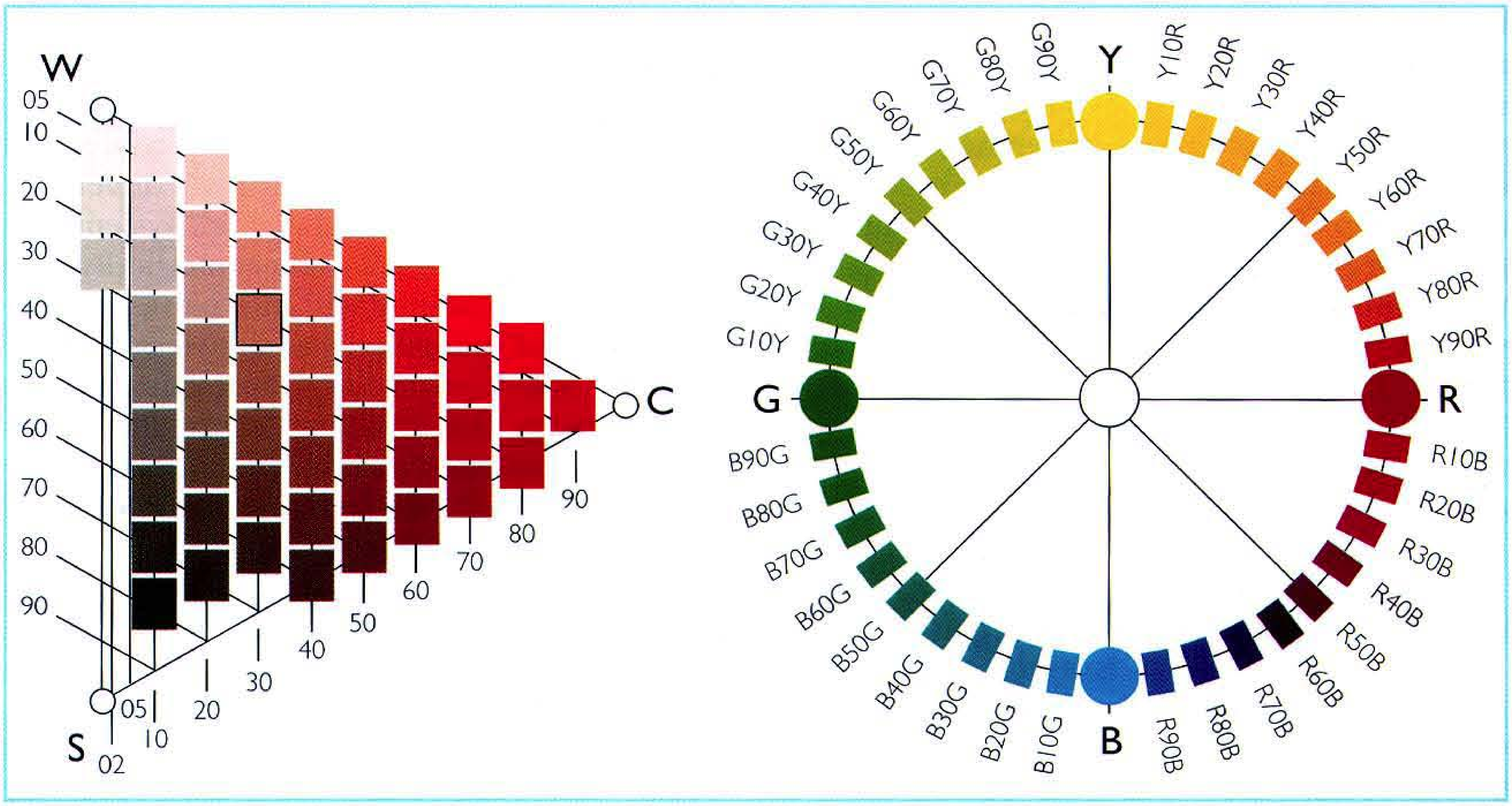


Figure 5.4 **(Left) Geometry of constant NCS hue Y90R. The sample outlined in black is 2030 Y90R. (Right) NCS hue circle. (Published with permission from the Scandinavian Colour Institute AB, Stockholm, Sweden. NCS – NATURAL COLOUR SYSTEM, Copyright © and trademark ®, property of Scandinavian Colour Institute AB, Stockholm, Sweden, 2001.)**

In the OSA/UCS system, every sample is defined by its values on three coordinates, L, j, and g. Roughly speaking, variation along the L coordinate corresponds to variation in lightness, variation on the j coordinate to variation in blueness/yellowness, and variation on the g coordinate to variation in redness/greenness. For the standard viewing conditions under which the scalings were performed (viewing under CIE illuminant D65 against a nonselective background of 30% reflectance), the Ljg coordinates of a sample may be computed from its CIE 1964 (10°) XYZ tristimulus coordinates. The XYZ coordinates of the sample are specified with respect to CIE illuminant D65 scaled so that a perfect diffuser has a Y coordinate of 100. The formulae for computing L are:[1]

$$L = \frac{(\mathcal{L} - 14.4)}{\sqrt{2}} \qquad (5.1)$$

$$\mathcal{L} = \begin{cases} 5.9[Y_0^{1/3} - 2/3 + 0.042|Y_0 - 30|^{1/3}], & Y_0 > 30 \\ 5.9[Y_0^{1/3} - 2/3 - 0.042|Y_0 - 30|^{1/3}], & Y_0 \leq 30 \end{cases}$$

$$Y_0 = Y(4.4934x^2 + 4.3034y^2 - 4.276xy - 1.3744x - 2.5643y + 1.8103)$$

where x and y are CIE chromaticity coordinates computed from the XYZ tristimulus coordinates. The formulae for computing j and g are:

$$\begin{aligned} j &= C(1.7R^{1/3} + 8G^{1/3} + 9.7B^{1/3}) \\ g &= C(-13.7R^{1/3} + 17.7G^{1/3} - 4B^{1/3}) \end{aligned} \qquad (5.2)$$

with

$$C = \frac{\mathcal{L}}{5.9[Y_0^{1/3} - 2/3]} \qquad (5.3)$$

$$\begin{aligned} R &= 0.7990X + 0.4194Y - 0.1648Z \\ G &= -0.4493X + 1.3265Y + 0.0927Z \\ B &= -0.1149X + 0.3394Y + 0.7170Z \end{aligned}$$

The Ljg coordinate dimensions form a rectilinear coordinate system. An interesting feature of the OSA/UCS system, however, is that the coordinates are intended to be sampled using a regular-rhombohedral scheme. This sounds complex, but may be accomplished by applying the simple rule that the L, j, and g coordinates for any sample are either all even integers or all odd integers, with zero being considered even (MacAdam, 1974). In the OSA/UCS system, chips that are equidistant nearest neighbors on the sampled lattice are designed to be equally salient from one another. One of the features of using this lattice structure is that it may be subsampled by a large number of different planes. Each plane provides a palette that may be useful for color selection (Cowan, personal communication). Figure 5.5 shows such planar sampling from the OSA/UCS space.

The size of color steps in the OSA/UCS lattice is about 20 just-noticeable-differences under the viewing conditions used by the committee. The committee concluded, however, that judgments of color discriminations are fundamentally non-Euclidean, so that they did not recommend their system for specification of color differences generally. That is, the committee recommended against using Euclidean distance in the Ljg coordinate space as a general color metric. Indeed, they concluded that no such metric could exist (MacAdam, 1974; see also Indow, 1980). This emphasis may have led to a lack of interest in the system, but one should bear in mind that the committee's conclusion applies not just to their own space but to any color difference space.

Note that the OSA/UCS system makes no explicit use of the concepts of color appearance. The scaling judgments used to define the space are entirely those of color difference. Although this may be a weakness for applications where intuitive descriptions of color are required, the space may still be used for appearance specification. Because the arrangement of colors in the space is regular, users may visually locate a desired sample in the space and find its OSA/UCS coordinates by interpolation.

5.2.2.3 DIN color system

The DIN system was developed as a German standard for color specification; a readable

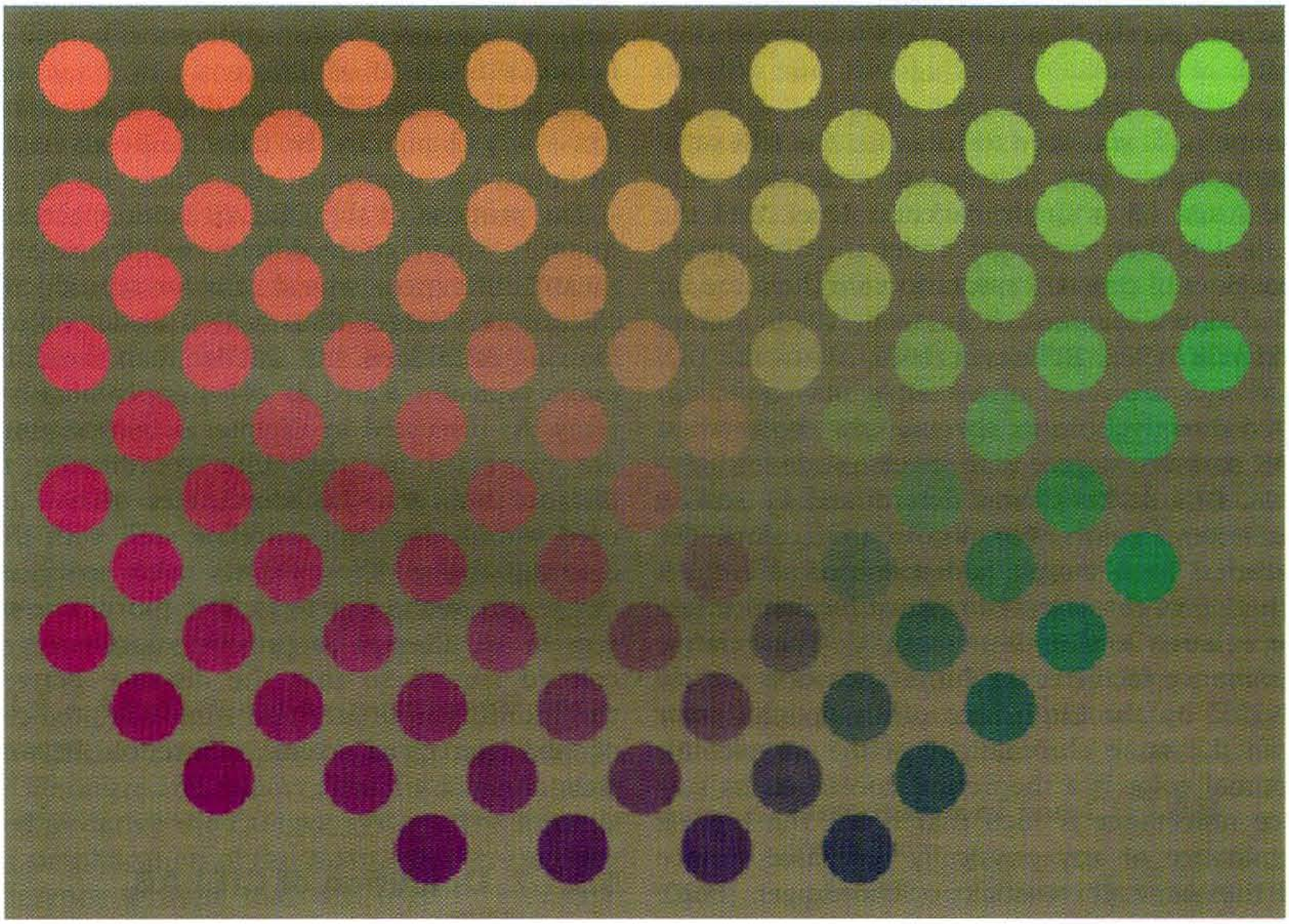


Figure 5.5 A plane of regularly spaced colors in the OSA/UCS space. The plane is constrained by the requirement that L = j. All coordinate values are integral. L values run from –5 to 6 (bottom to top) while g values run from –10 to 6 (left to right).

description may be found in a historical review by Richter and Witt (1986). The principles underlying the DIN system are very similar to those of the Munsell system, with the interesting variation that a number of colorimetric constraints were imposed to make the system more convenient to use (Richter and Witt, 1986; Billmeyer, 1987; Derefeldt, 1991). As with the Munsell, NCS, and OSA/UCS systems, the DIN system is implemented in a color atlas (DIN, 1980).

The three perceptual variables of the DIN system are hue, saturation, and darkness. The DIN hue scale for a single saturation and darkness was constructed from scaling data, much in the same way as Munsell hue. Rather than extending the scale to other saturations and lightnesses through further scaling experiments, however, DIN hue was defined to be constant for lines of constant dominant and complementary wavelength (with respect to CIE Illuminant C: Richter and Witt, 1986; Billmeyer, 1987). This simplification makes the transformation between tristimulus coordinates and DIN hue straightforward, at the cost of making DIN hue only an approximate measure of perceived hue. A similar compromise was used to construct the DIN saturation scale. Lines of constant saturation were measured for a single darkness level, and the scale was then extended under the assumption that lines of constant saturation are the same for all darkness degrees (Robertson, 1984; Richter and Witt, 1986; Billmeyer, 1987). Thus the DIN hue and saturation of a sample may be calculated directly from its chromaticity coordinates. DIN darkness degree is an inverse scale for lightness. DIN darkness was determined by scaling for neutral colors. For non-neutral colors, the darkness for a sample is determined as a direct function of the sample's relative luminance factor relative to CIE Illuminant C. The relative luminance factor is the luminance of a sample divided by the luminance of an optimal color with the same chromaticity of the sample. An optimal color is a theoretical construct. Its surface reflectance is such that it has the highest luminance of any physically realizable surface of the same chromaticity (Schrodinger, 1920; Rosch, 1928; MacAdam, 1935; Wyszecki and Stiles, 1982; Richter and Witt, 1986). Again, this is a convenient approximation which simplifies the calculation of DIN darkness degree.

5.3 COLOR DIFFERENCE SYSTEMS

5.3.1 EXAMPLE: CIELAB COLOR SPACE

5.3.1.1 Problem – specifying color tolerances

In writing contracts for color reproduction, it is important to be able to specify how accurately a color must be reproduced. To do this, it is necessary to have an objective metric for measuring color differences. There are several levels at which one might want to specify color tolerances. For precise applications, one might want to know how large a measured color difference has to be before observers can reliably detect it. This size of difference is often referred to as a just-noticeable-difference. On the other hand, if one is worried about reproducing the characteristic color associated with, say, a particular brand, one might want to know how large a measured color difference has to be before it is classified differently by customers. Detectable color differences do not necessarily cause any change in the color name given to a stimulus.

The purpose of the CIELAB color space is to quantify small color differences. By small is meant differences typical of color reproduction tolerances – larger than a JND under optimal viewing conditions, but smaller than the differences typically scaled in color appearance systems. As discussed in Chapter 3, when stimuli are expressed in tristimulus coordinates, the distance between the coordinates of two colored stimuli does not correlate well with their discriminability. The CIELAB color space was derived from the CIE 1931 XYZ coordinate system in an attempt to provide coordinates for colored stimuli so that the distance between the coordinates of any two stimuli is predictive of the perceived color difference between them.

5.3.1.2 Definition of CIELAB

The CIELAB coordinates of a light are referred to as the CIE 1976 L*a*b* coordinates. These may be obtained from the light's CIE 1931 XYZ coordinates according to the equations

$$L^* = \begin{cases} 116\left(\frac{Y}{Y_n}\right) - 16, & \frac{Y}{Y_n} > 0.008856 \\ 903.3\left(\frac{Y}{Y_n}\right), & \frac{Y}{Y_n} \leq 0.008856 \end{cases}$$

$$a^* = 500\left[f\left(\frac{X}{X_n}\right) - f\left(\frac{Y}{Y_n}\right)\right] \qquad (5.4)$$

$$b^* = 500\left[f\left(\frac{Y}{Y_n}\right) - f\left(\frac{Z}{Z_n}\right)\right]$$

where the function f(s) is defined as

$$f(s) = \begin{cases} s^{1/3}, & s > 0.008856 \\ 7.787(s) + \frac{16}{116}, & s \leq 0.008856 \end{cases} \qquad (5.5)$$

In this equation, the quantities X_n, Y_n, and Z_n are the tristimulus coordinates of a white point. Little guidance is available as to how to choose an appropriate white point. In the case where the stimuli being judged are illuminated samples, the tristimulus coordinates of the illuminant may be used. In the case where the lights being judged are displayed on a color monitor, the sum of the tristimulus coordinates of the three monitor phosphors stimulated at their maximum intensity may be used.

The Euclidean distance between the CIELAB coordinates of two lights provides a rough guide to their discriminability. The symbol ΔE^*_{ab} is used to denote distance in the uniform color space and is defined as

$$\Delta E^*_{ab} = \sqrt{(\Delta L^*)^2 + (\Delta a^*)^2 + (\Delta b^*)^2} \qquad (5.6)$$

where the various Δ quantities on the right represent the differences between the corresponding coordinates of the two stimuli.

5.3.1.3 Underlying experimental data

It is difficult if not impossible to go back through the literature and discover the fundamental data used to derive the CIELAB system. The formula is a simplification of the Adams–Nickerson color difference formula that was used in industrial practice prior to 1976 (McLaren, 1970, 1971). Robertson (1977) compares the CIELAB formula with two fundamental data sets. The first of these is the spacing of the Munsell colors. Figure 5.6 plots the CIELAB a*b* coordinates of contours of equal Munsell chroma and lines of constant Munsell hue. If the two spaces were consistent with each other, the contours of constant chroma would be circles and the radial spacing between lines of constant hue would be constant at each chroma. As the figure illustrates, the agreement between the two spaces is only approximate. Another comparison data set is the MacAdam ellipses, which measure the just-noticeable color differences (MacAdam, 1942; see Chapter 3). If CIELAB accurately represents uniform color differences, these should plot as circles in the CIELAB space. Figure 5.6 also shows the MacAdam ellipses plotted in the CIELAB space. Clearly these are not circular. As Robertson (1977) points out, the lack of agreement between CIELAB and the Munsell/MacAdam data could arise because CIELAB is designed to handle color differences of a magnitude intermediate between the spacing of Munsell samples and just-noticeable-differences.

To provide a feel for the scale of ΔE^*_{ab}, we can compute the average ΔE^*_{ab} value corresponding to measured just-noticeable color differences. Wyszecki and Stiles (1982) provide the parameters for color difference ellipses measured around 25 different chromaticities by MacAdam (1942). The ellipses represent variability in observers' color matches. From the ellipse parameters it is possible to compute the value of ΔE^*_{ab} that corresponds to traversing 1.96 standard deviations along the major and minor axis of each ellipse. The average resulting value is 3.6, with a range of 0.9 to 9.9. Consistent with this, Stokes, Fairchild, and Berns (1992) report that when the average (taken over image locations) ΔE^*_{ab} difference between two images is below about 2.2, the images are not discriminably different from each other. To give a visual sense for the scale of ΔE^*_{ab}, Figure 5.7 shows several series of colors separated by constant CIELAB differences.

5.3.1.4 Discussion of the CIELAB system

There is general agreement that using the CIELAB system is an improvement over using the Euclidean distance between XYZ tristimulus coordinates as a color difference metric. To emphasize the difference between CIELAB and

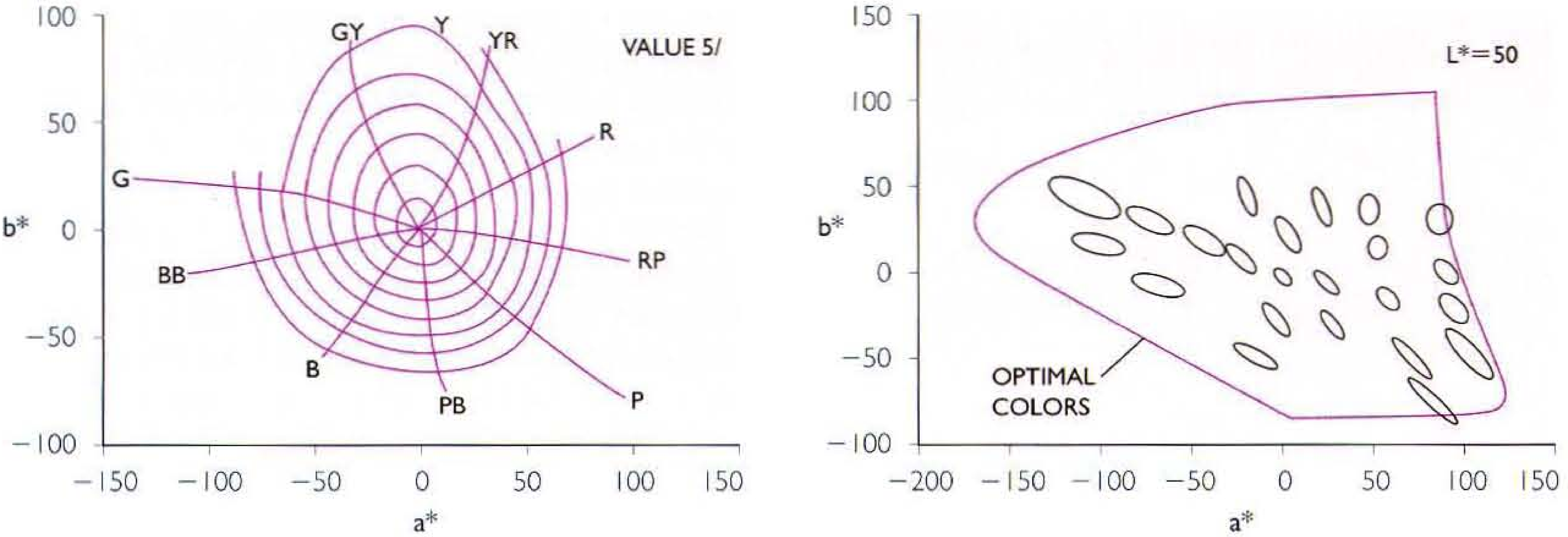


Figure 5.6 **(Left) Contours showing equal Munsell chroma and iso-hue lines plotted in CIELAB coordinates. (Right) A plot of the CIELAB coordinates of isodiscrimination contours measured by MacAdam. The scale of each ellipse has been expanded to improve the visibility of its shape. (From Robertson, 1977. Copyright © 1984 John Wiley & Sons, Inc., reproduced by permission.)**

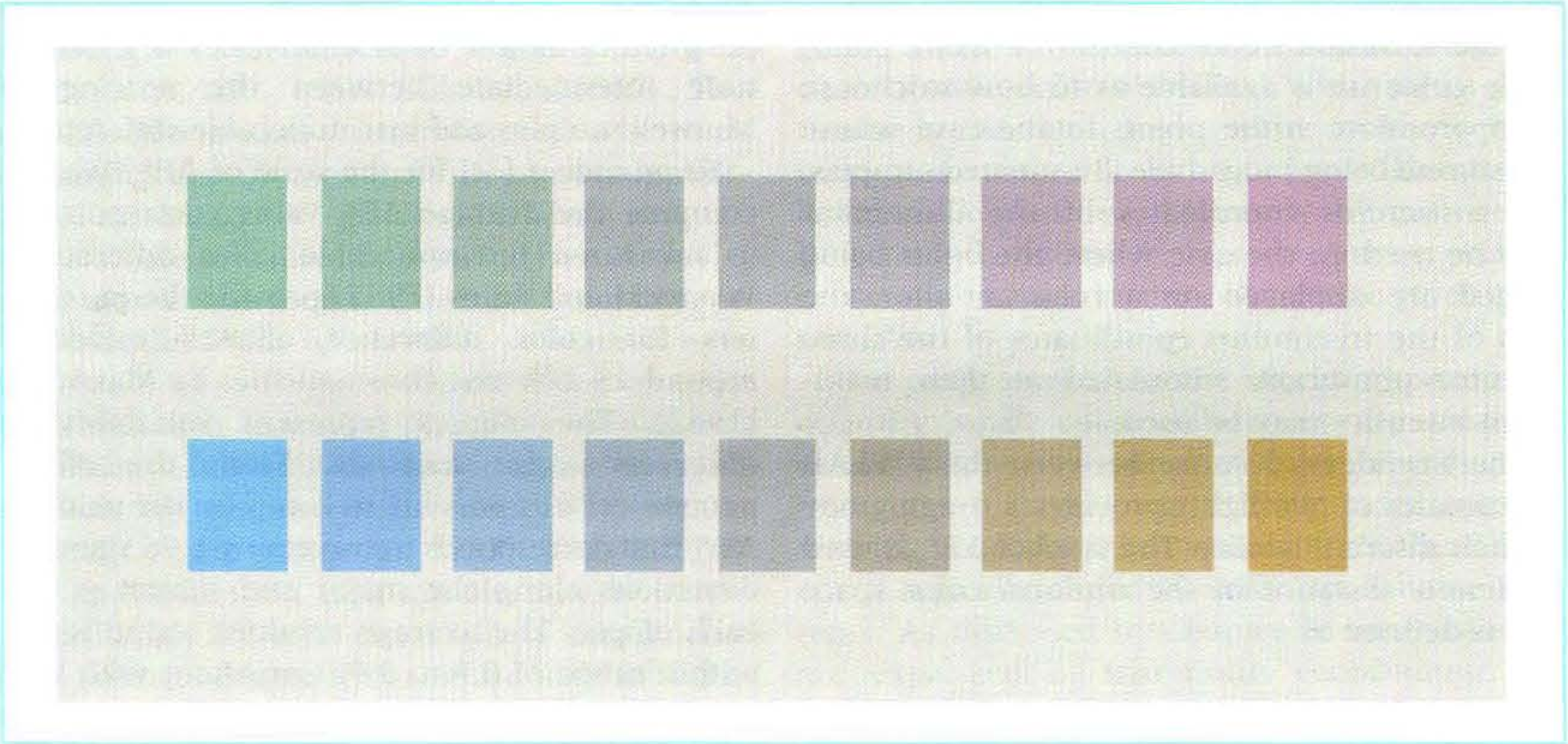


Figure 5.7 **Each row shows a series of colors separated by constant CIELAB differences. First row shows CIELAB $\Delta E^*_{ab} = 4$ along the a* dimension, second row shows CIELAB $\Delta E^*_{ab} = 12$ along the b* dimension. CIELAB coordinates were computed with respect to a white point defined by the background of the figure.**

tristimulus coordinates, Figure 5.8 shows isodiscrimination contours calculated using equal ΔE^*_{ab} values. The contours are plotted in the equiluminant XZ plane of the CIE XYZ color space. If the two distances in XYZ and CIELAB both represented perceptual color differences, the contours would plot as circles. Clearly, they do not.

Since its initial standardization, predictions of the CIELAB system have been compared to new measurements. These have led to a revision of the original system. The CIE has recommended one of these revisions, CIE94 (CIE, 1995; Hung and Berns, 1995). A second revision in widespread use is the CMC formula (Clark *et al.*, 1984). In the CIE94 system, a distance measure ΔE^*_{94} is substituted for ΔE^*_{ab}. To understand the computation of ΔE^*_{94}, first note that we can rewrite Eqn. 6 as

$$\Delta E^*_{ab} = \sqrt{(\Delta L^*)^2 + (\Delta C^*_{ab})^2 + (\Delta H^*_{ab})^2} \quad (5.7)$$

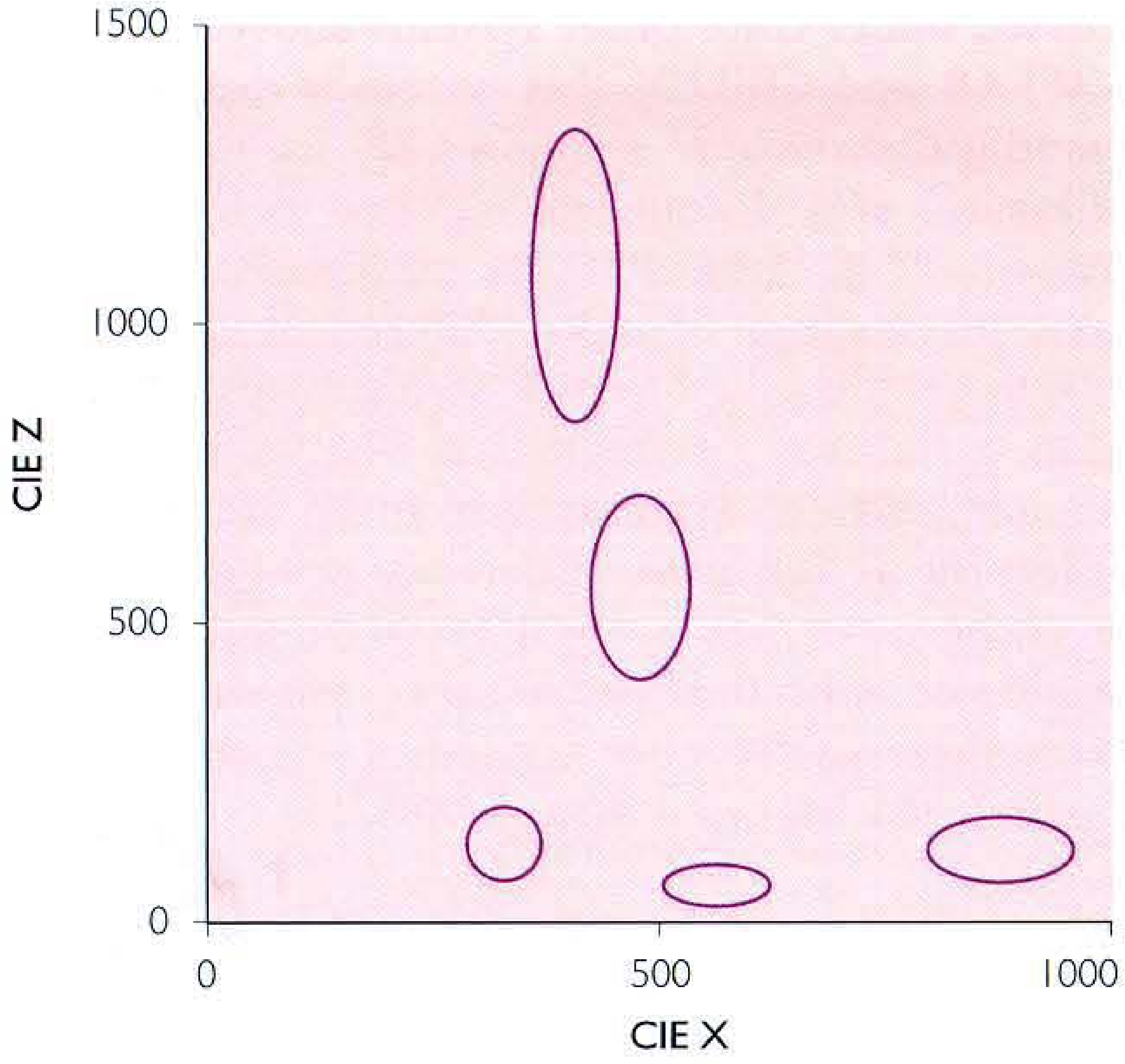


Figure 5.8 **Isodiscrimination contours calculated using equal ΔE^*_{ab} values plotted in the XZ plane of the CIE XYZ color space. The points on each of the five contours were calculated to have a constant ΔE^*_{ab} difference of 15 from a base stimulus. The conversion from XYZ coordinates to CIELAB coordinates was done with respect to a white point with the same chromaticity as CIE D65 daylight and a luminance of 1000 cd/m^2. The luminance of the base stimuli was always taken to be 500 cd/m^2. The contours were computed in the equiluminant XZ plane. If CIELAB and CIE XYZ agreed about color differences, the contours would plot as circles.**

where the chroma coordinate C^*_{ab} is defined by $C^*_{ab} = \sqrt{(a^*)^2 + (b^*)^2}$, where ΔC^*_{ab} denotes the difference in the C_{ab} coordinate of the two stimuli, and where the hue difference ΔH^*_{ab} is defined by $\Delta H^*_{ab} = \sqrt{\Delta E^*_{ab} - \Delta L^* - \Delta C^*_{ab}}$. The CIE94 difference measure ΔE^*_{94} is computed as a modification of Eqn. 7:

$$\Delta E^*_{94} = \sqrt{\left(\frac{\Delta L^*}{k_L S_L}\right)^2 + \left(\frac{\Delta C^*_{ab}}{k_C S_C}\right)^2 + \left(\frac{\Delta H^*_{ab}}{k_H S_H}\right)^2}. \quad (5.8)$$

In equation 5.8 the S weighting factors are defined as, $S_L = 1$, $S_C = 1 + 0.045C^*_{ab\_s}$ and $S_H = 1 + 0.015C^*_{ab\_s}$ where $C^*_{ab\_s}$ is the chroma coordinate of the standard sample from which differences are being computed.[2] The k weighting factors are all set to 1 for the reference viewing conditions[3] but may be modified at the user's discretion for other viewing conditions. Further refinement of CIELAB-based systems can be expected and future versions may provide more precise guidance about the choice of the k weighting factors.

Although the CIELAB system was designed for specification of color tolerances, it has been used to assess color differences in other contexts (Carter and Carter, 1981; Silverstein and Merrifield, 1981). In the absence of better formulae, this is a reasonable thing to do. However, it should be stressed that the formulae are not grounded in empirical data that support these other uses. Figure 5.6 gives useful comparisons to keep in mind.

As noted above, one of the chief difficulties in developing a color difference specification system is to take the viewing conditions into account. Color discrimination thresholds depend heavily on factors other than the differences in tristimulus coordinates. These factors include the adapted state of the observer (Stiles, 1959), the spatial and temporal structure of the stimulus (deLange, 1958a, 1958b; Mullen, 1985; Sekiguchi *et al.*, 1993) and the perceptual task being performed by the observer (Carter and Carter, 1981; Silverstein and Merrifield, 1985; Poirson and Wandell, 1990; Nagy and Sanchez, 1990). The basic CIELAB formulae include normalization to a white point which is designed to take the first of these factors into account. At present, however, our understanding of observer adaptation is not sufficiently well developed to make us believe that the CIELAB formulation is satisfactory (see Brainard and Wandell, 1991; Fairchild, 1998).

Zhang and Wandell (1997) have developed an extension of CIELAB, called S-CIELAB, which takes the spatial structure of the stimulus into account. S-CIELAB is based on psychophysical measurements showing that visual sensitivity to spatial gratings falls off more rapidly with grating spatial frequency when the gratings are modulated in some color directions (e.g. red–green and blue–yellow gratings) than when they are modulated in others (e.g. black/white gratings: Mullen, 1985; Sekiguchi *et al.*, 1993). The S-CIELAB metric is computed in two separable stages, based on the data and model of Poirson and Wandell (Poirson and Wandell, 1996). The first stage computes the effect of spatial structure on the discriminability of different chromatic components of an image. The second stage applies the standard CIELAB metric to the output of the first stage. The S-CIELAB metric does a better job of predicting observers' judgments of the perceptual differences between color images than the unmodified CIELAB metric, but it is clear that further development is required (Zhang and Wandell, 1998).

The CIELAB system was not designed to be a color appearance system. Although it does define scales for hue, chroma, and lightness, these scales are only approximate and are not as well grounded in appearance data as most color order systems or color appearance models.

5.3.2 OTHER COLOR DIFFERENCE SYSTEMS

5.3.2.1 CIELUV

At the time the CIELAB standard was introduced, the CIE also introduced a second system for specifying small color differences. This is called the CIELUV system, and coordinates in this system are referred to as the CIE 1976 L*u*v* coordinates. Like the CIELAB system, the CIELUV system was derived from systems used widely in practice prior to the standardization. CIELUV coordinates are derived from tristimulus coordinates as well. The formulae for computing CIELUV coordinates may be found in numerous publications (Wyszecki and Stiles, 1982; CIE, 1986). At the time of standardization, the CIE recognized that it was difficult to choose between the two systems, as each worked better on different validation data sets and each had its proponents. Indeed, the general feeling in the color community was that no color difference system explained more that about 80% of the variance in color discrimination data, and that each system explained a different 80% (Cowan, personal communication). More recently, opinion has tended to favor the CIELAB system and its successor CIE94, and the CIELUV system is no longer widely recommended (Fairchild, 1998).

5.3.2.2 Color order systems

The OSA/UCS color order system may be thought of as a color difference system. This system was designed to apply larger color differences than either CIELAB or CIELUV. It is discussed under color order systems above. As with CIELAB and CIELUV, this system is designed to handle cases where samples vary in both chromaticity and luminance. Other color order systems (e.g. Munsell, DIN) are based at least in part on scalings of color differences, as when observers are asked to pick a chip whose saturation is halfway between that of two reference samples. These systems are more difficult to interpret as full color difference systems, however, because they are not based on data where multiple stimulus attributes are covaried. Nonetheless, they are sometimes used in this fashion (Richter and Witt, 1986).

5.4 CURRENT DIRECTIONS IN COLOR SPECIFICATION

5.4.1 CONTEXT EFFECTS

As illustrated in Figure 5.2, implementations of color order systems may be thought of as lookup tables that specify the relation between color appearance and physical samples. As such, these implementations embody knowledge about the psychology of color appearance. The implementations, however, depend on scaling experiments conducted using a well-specified viewing context. This is emphasized in Figure 5.2 by the fact that the viewing conditions are specified along the arrow linking the two sides of the table. Clearly, it would be useful to be able to specify color appearance for conditions other than the standard. Of particular interest is the prediction of the appearance of images, where the stimulus at each location is viewed in the complex surround defined by the rest of the image. Because the effects of context can be quite large (Figure 5.9), neglecting them can lead to large prediction errors.

In general, both the appearance and discriminability of colored stimuli depend on the context in which the stimuli are viewed (see Chapters 3 and 4). Because our understanding of context effects is incomplete, it is not yet possible to incorporate precisely the effects of context into color specification systems. It is possible to lay out a general framework that allows us to incorporate what is known about the effect of

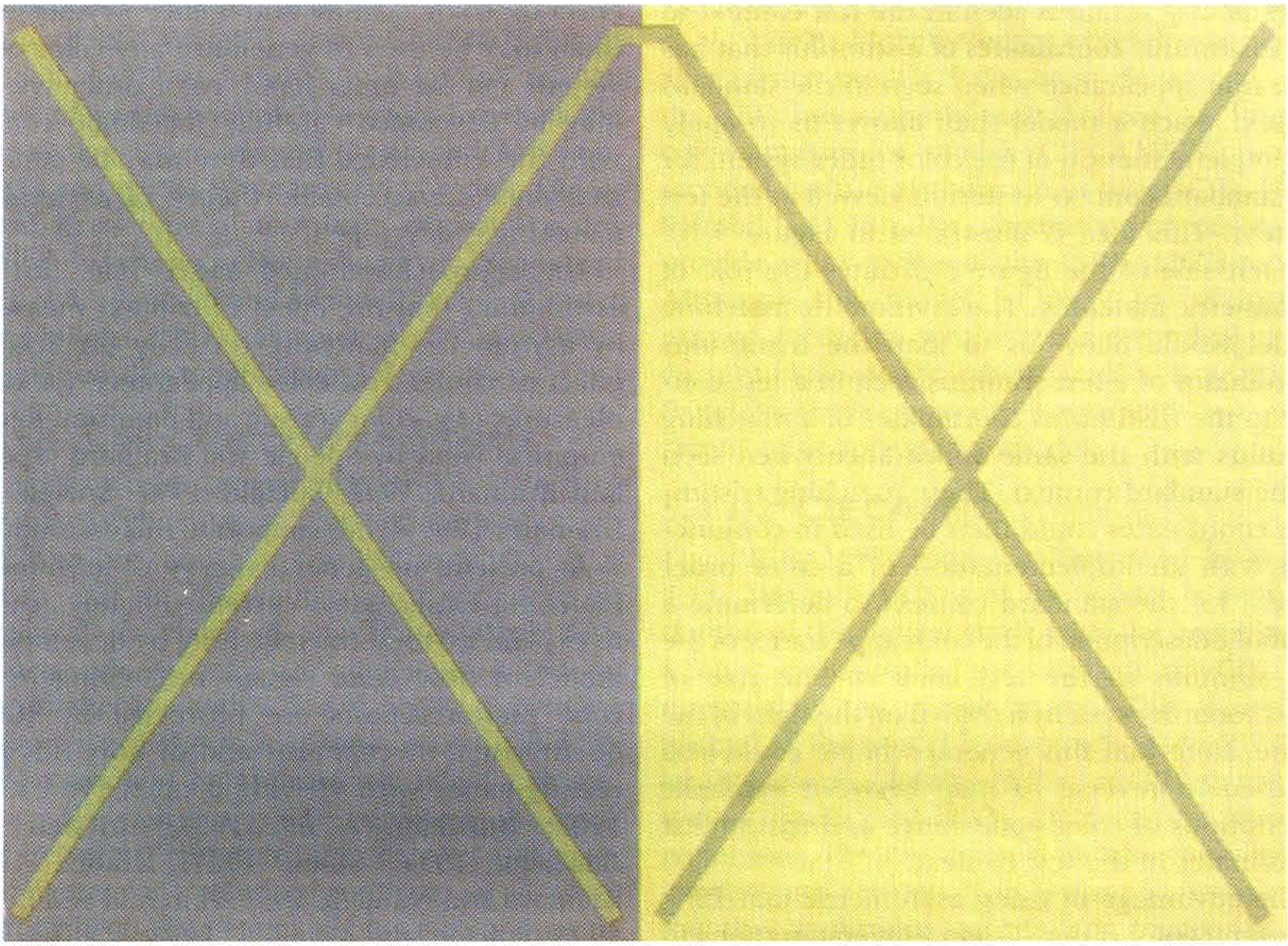


Figure 5.9 **Illustration of context effects. The x-shaped intersections on the two sides of the figure appear quite different. The light reaching the eye from these two regions is the same, however. This can be seen by tracing from one x-shaped region to the other. (From Albers, 1975. Copyright © 1975 Yale University Press, reproduced with permission.)**

context into current color order and discrimination systems. This framework provides the foundation for current work towards developing color appearance models. The key to this framework is asymmetric color matching.

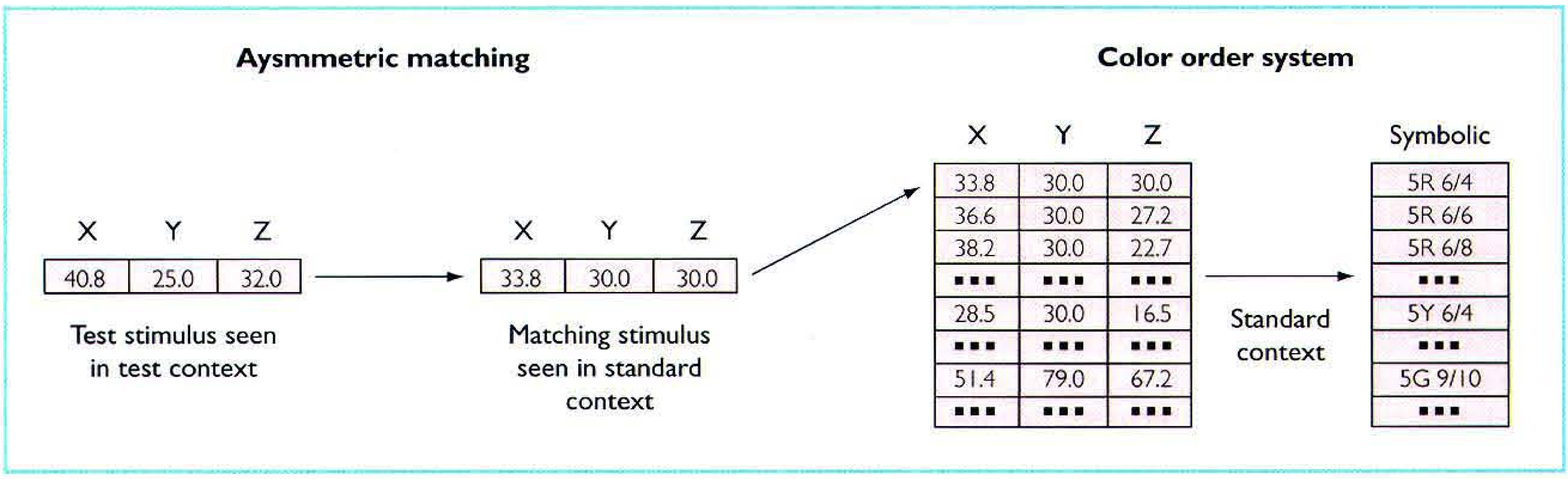
Asymmetric color matching is an experimental procedure that may be used to establish pairs of stimuli that match across changes in viewing context (von Kries, 1902; Burnham *et al.*, 1957; Stiles, 1967; Krantz, 1968; Brainard and Wandell, 1992; Poirson and Wandell, 1993; Webster and Mollon, 1995). In an asymmetric matching experiment, the observer adjusts the color of one stimulus, seen in some arbitrary context, to match the appearance of a standard stimulus seen in a standard context. By setting such matches, the observer establishes pairs of stimuli that, across contexts, have the same appearance. The two contexts may be separated spatially or in time, but in either case the observer need only judge identity of color appearance; the complex structure of appearance scaling judgments does not intrude into the experiment.

Let us use the term standard context to refer to a set of viewing conditions for which we have implemented a color order system. Typically, the standard context consists of viewing a single sample at a time against a uniform gray background, under a well-specified illuminant. Let us use the term test context to refer to some other set of viewing conditions for which we would like to specify color appearance. Suppose that we are able to develop a descriptive model that predicts observers' asymmetric matches between any two contexts. In particular, this model should allow us to relate the tristimulus coordinates of any stimulus seen in the test context to the tristimulus coordinates of a stimulus that has the same appearance when seen in the standard context. Such a model then allows us to apply the implementation of the color order system for the standard context to stimuli viewed in the test context. This idea is illustrated in Figure 5.10. The left side of the figure illustrates the role of asymmetric matching. The asymmetric matching model would allow us to map the tristimulus coordinates of a test stimulus seen in a test context to the tristimulus coordinates of a matching stimulus with the same appearance when seen in the standard context. These matching tristimulus coordinates could then be used in conjunction with an implementation of a color order system for the standard context to determine a symbolic description of the color appearance of the test stimulus in the test context. The role of the color order system is shown on the right of the figure. Note that this general scheme could also be used in reverse to map between symbolic descriptions of color appearance and tristimulus coordinates in the test context.

The advantage of using asymmetric matching to extend color order system implementations to general viewing contexts is that it separates the problem of understanding context from the problem of implementing a color order system. On the one hand, the asymmetric matching experiments may be conducted without reference to color names and hence results from them may be used to generalize any color order system. On the other hand, color order systems may be developed carefully for single context with the knowledge that they may be generalized once an acceptable theory of asymmetric matching is developed.

The approach outlined above relies on the assumption that the effect of context measured by asymmetric matching correctly predicts the effect of context on color appearance for other measures (e.g. color scaling and naming). Recent empirical work by Speigle and Brainard (Speigle and Brainard, 1996; Speigle, 1997; Speigle and Brainard, 1999) lends support to this assumption.

At present, no general theory of asymmetric matching exists. Most current theories attempt to explain asymmetric matching by developing a model of how color signals originating in the cone photoreceptors are processed by subsequent visual mechanisms and of how this processing varies with viewing context (von Kries, 1902; Burnham *et al.*, 1957; Hurvich and Jameson, 1957; Stiles, 1967; Krantz, 1968; Brainard and Wandell, 1992; Fairchild and Berns, 1993; Poirson and Wandell, 1993; Webster and Mollon, 1995; Delahunt and Brainard, 2000). The simplest model goes back to von Kries, who suggested that the effect of context was simply to scale the cone signals independently for each



X	Y	Z
40.8	25.0	32.0

X	Y	Z
33.8	30.0	30.0

X	Y	Z	Symbolic
33.8	30.0	30.0	5R 6/4
36.6	30.0	27.2	5R 6/6
38.2	30.0	22.7	5R 6/8
■■■	■■■	■■■	■■■
28.5	30.0	16.5	5Y 6/4
■■■	■■■	■■■	■■■
51.4	79.0	67.2	5G 9/10
■■■	■■■	■■■	■■■

Figure 5.10 Schematic of how asymmetric matching can be used to extend a color order system to other contexts. The left side of the figure illustrates the role of asymmetric matching. A general characterization of asymmetric matching would allow us to map the tristimulus coordinates of a test stimulus seen in a test context to the tristimulus coordinates of a matching stimulus with the same appearance when seen in the standard context. These matching tristimulus coordinates could then be used in conjunction with an implementation of a color order system for the standard context to determine a symbolic description of the color appearance of the test stimulus in the test context. The role of the color order system is shown on the right of the figure.

cone type (von Kries, 1905). This class of model accounts well for a subset of color context effects (Brainard and Wandell, 1992; Chichilnisky and Wandell, 1997) and Land's well-known retinex theory of context vision is a special case of the general von Kries scheme (Land and McCann, 1971; Land, 1986; Brainard and Wandell, 1986). A von Kries type of transform cannot account for all color context effects, however (Krauskopf *et al.*, 1982; Poirson and Wandell, 1993; Webster and Mollon, 1995). Chapter 4 discusses basic research on this topic in more detail.

5.4.1.1 Color appearance models

The goal of color appearance models is to provide an analytic relation between a specification of a stimulus and the context in which it is viewed and its color appearance (in terms of numerical correlates of appearance attributes). As such, color appearance models must contain components for both sides of Figure 5.10. One component of the model must account for the effect of context on appearance, while a second must provide an analytic description of the mapping between tristimulus coordinates and symbolic names for a standard context.

An early attempt at developing a color appearance model was made by Judd (Judd, 1940). Second generation models were developed by Hunt (Hunt, 1982; Hunt and Pointer, 1985; Hunt, 1987a, 1987b, 1991) and by Nayatani and his coworkers (Nayatani, Takahama, and Sobagaki, 1981; Nayatani, Sobagaki, and Takahama, 1986; Nayatani *et al.*, 1987; Nayatani *et al.*, 1990). More recently, several other color appearance models have been developed, and the CIE has recently standardized an interim color appearance model, CIECAM97s, recommended for use at the current time (CIE, 1998; Fairchild, 1998). For illustrative purposes, we provide an overview of the CIECAM97s model. Although this model is likely to be further refined, its design synthesizes a great deal of our current knowledge about color appearance. Fairchild (1998) provides a thorough review of recent color appearance models.

5.4.1.2 CIECAM97s

The CIECAM97s model is illustrated in Figure 5.11. The initial stage of the model (shown on the top of the figure) starts with the encoding of a test stimulus (called the source in the CIE documents) by the visual system. This is accomplished in the model by computing the CIE XYZ tristimulus coordinates of the test. These coordinates are indicated in the figure by the grouped rectangles. The next step is to take the viewing context into account. This is done by transforming the tristimulus coordinates to coordinates that represent the adapted cone responses of a stimulus that would match the source, when it was seen under standardized reference viewing conditions. The transformation takes context into account and results in a representation of

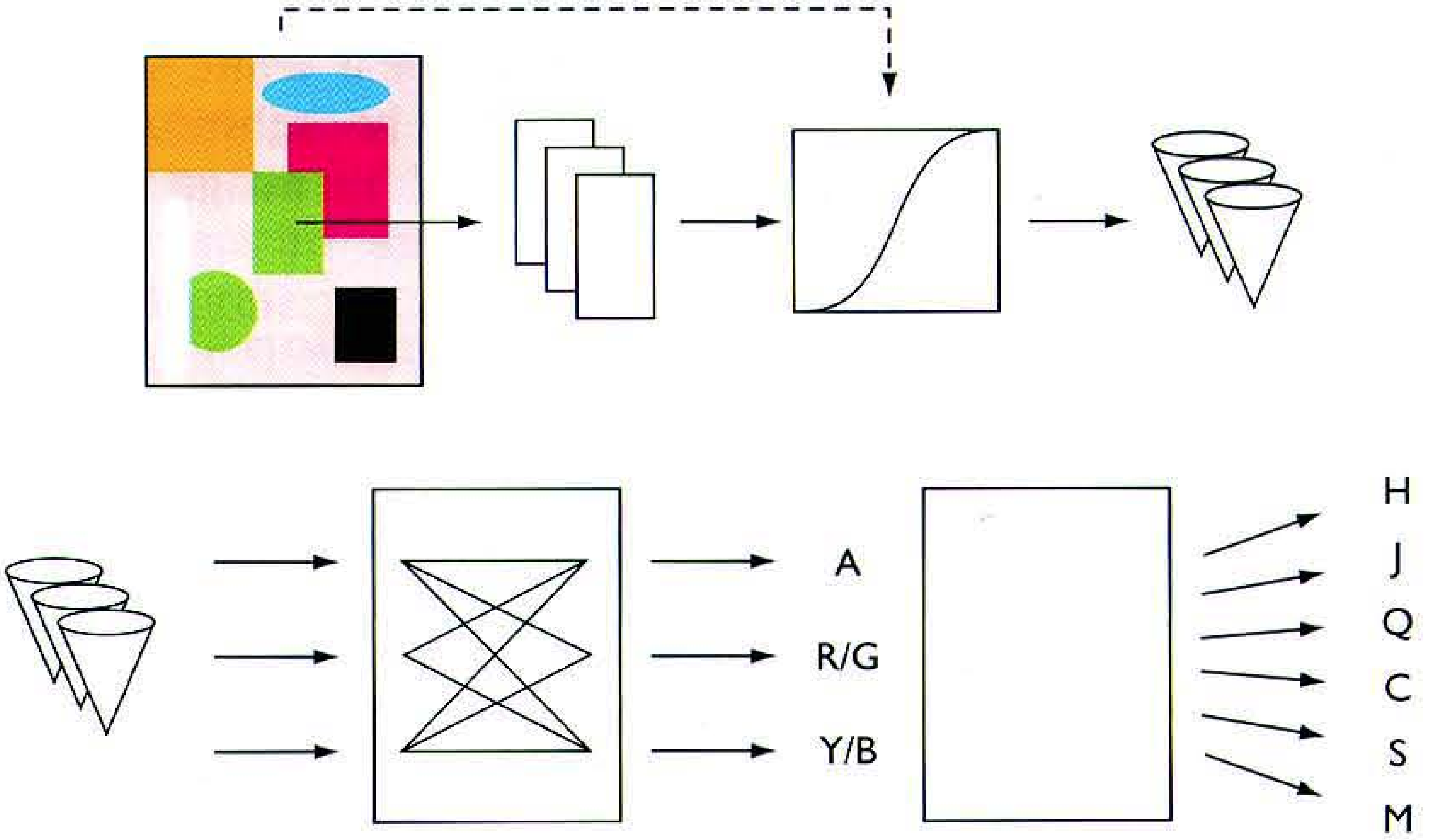


Figure 5.11 Schematic illustration of the CIECAM97s color appearance model. See description in the text.

the test in terms of the L, M, and S cone photoreceptor responses. The actual calculation of the adapted cone responses is somewhat involved and depends on the context in which the test is seen. It is illustrated in the figure by the sigmoidal nonlinearity. The arrow from the context to the nonlinearity indicates that the transformation depends on the context. To apply the model in practice involves a certain degree of art, as the user must set a number of parameters that specify the completeness of adaptation to the viewing context. The adapted cone responses are the output of the first stage of the model and are shown schematically in the figure by the grouped cones.

The first stage of the CIECAM97s model is analogous to the first stage in the asymmetric matching framework described above. The only difference is that rather than mapping the tristimulus coordinates of the test to those of a matching stimulus, it maps the tristimulus coordinates of the test to adapted cone responses. The adapted cone responses can, however, be associated with the tristimulus coordinates of a matching stimulus in the reference context by applying the inverse of the first stage with the parameters set for the reference context.

The purpose of the second stage of CIECAM97s is to provide an analytic description of how the adapted cone coordinates relate to color appearance attributes. It is based on an opponent process model of how subsequent visual mechanisms process the adapted cone signals. The key idea is that signals originating in the three classes of cones are recombined to form a non-opponent achromatic signal and opponent chromatic signals. The opponent process model was articulated in the modern literature by Hurvich and Jameson (Hurvich and Jameson, 1957; Jameson and Hurvich, 1955, 1964), who used it to explain a large number of color appearance phenomena. It is lent credence by the fact that observers can make judgments that may be interpreted as tapping solely the chromatic mechanisms (Jameson and Hurvich, 1955, 1964; Larimer *et al.*, 1974, 1975; Krantz, 1975; Walraven, 1976; Shevell, 1978; Werner and Walraven, 1982; Shevell and Wesner, 1989). In the model, each of the opponent signals is formed as a weighted combination of the adapted cone signals. The achromatic signal (indicated by A in the figure) is formed as the weighted sum of the three adapted cone signals. The red/green signal (R/G) is obtained by opposing signals from adapted L and S cones with signals from adapted M cones. The yellow/blue signal (Y/B) is obtained by opposing signals from adapted L and M cones with signals from adapted S cones.

To produce color appearance descriptions, the model provides a set of transformations between A, R/G, and Y/B and scales for appearance attributes. Included are scales for hue (H), lightness (J), brightness (Q), chroma (C), saturation (S), and colorfulness (M).

The second stage of the CIECAM97s model is analogous to the second stage of the asymmetric matching framework described above. Note, however, that the lookup table description has been replaced by an analytic characterization between the adapted cone responses and the appearance scales. A second difference, neglected above, is that in CIECAM97s the relation between adapted cone responses and the appearance scales does contain a dependence on viewing context. For example, the scale for lightness depends on a comparison of the achromatic signal of the test and the achromatic signal for an image region designated by the user as white. This dependence means that in CIECAM97s, there is not complete separation between the effect of context and the transformation between adapted cone signals and appearance scales. This separation could be restored if the model of asymmetric matching accurately predicts the match to a white sample, since then the adapted cone signals for a white seen in the reference context could be substituted for the adapted cone signals of an image region designated by the user as white.

5.4.1.3 Discussion

CIECAM97s is interesting in that it attempts to bridge basic research on the nature of visual processing with applied research on color order systems. The greatest difficulty for testing and developing this (or any other) color appearance model is the huge array of possible viewing contexts that must be studied. Contextual factors that influence color appearance include both the size and shape of the stimulus itself, its local and global surround, and the adapted state of the observer. Our current understanding is based primarily on experiments where isolated test stimuli are viewed against uniform backgrounds of varying chromaticities and luminances. The difficulty is that it is not clear how to generalize from these experiments to more complicated viewing situations. Overcoming this difficulty is a prerequisite for a complete color appearance model and research on methods for doing so is ongoing (see Chapter 4). Note that if a color appearance model contains a successful model of context effects, this model could be used together with the asymmetric matching framework described above to extend color order systems to multiple contexts.

A particularly important area of application for color appearance models is to describe the appearance of stimuli presented on CRT displays. A great deal of image previewing and manipulation is now done using such displays, with the ultimate goal of printing a hard copy of the image. Ideally, it would be possible to make a reproduction of the CRT image that had exactly the same appearance as the original. This goal will probably not become easily achievable, however, until it is possible to describe both original and reproduced images in color appearance terms. As color appearance models are refined, they are likely to play increasing roles in automated color reproduction. (See Chapter 8 for a discussion of color reproduction.)

5.4.2 METAMERISM

5.4.2.1 The problem of metamerism

An important issue that arises in using color specification systems is the following. Current color specification systems are based on tristimulus coordinates. This presents no difficulties if one's goal is to use the system to produce a sample that will be viewed only under a single illuminant. One designs the sample to produce the desired tristimulus coordinates under the desired illuminant and the actual reflectance function of the sample is irrelevant (see Chapters 3 and 4). But what if the sample is to be viewed under more than one illuminant? For example, what if the specification is for the color of a car, which will be seen under a variety of daylights (and perhaps under artificial lighting at night)? The stability of the color appearance will depend on which reflectance function is chosen initially. How should the designer make this choice? This is the problem of metamerism.

5.4.2.2 Colorant order systems?

A brute force approach is provided by colorant order systems (Judd and Wyszecki, 1975). These are systems that are in many ways like color order systems. The difference is that these systems are not implemented in terms of tristimulus coordinates. Rather, their implementation is provided directly in terms of amounts of particular pigments, dyes, or inks. The advantage of a colorant order system is that a designer may choose a sample from it and be guaranteed that the final production will behave under different illuminants exactly as the sample. Thus the designer is restricted a priori to choosing among a set of producible samples, rather than choosing from a set of specifications that have multiple possible implementations. By investigating how various samples appear under different illuminants, the designer may use samples from colorant order systems to produce acceptable results.

The disadvantage of colorant order systems is that their use is confined to the output medium for which they were implemented. This limits the amount of effort that can go into their implementations and tends to make each such system idiosyncratic.

5.4.2.3 Metamerism indices

The goal of a metamerism index is to help designers reproduce a target sample so that the behavior of the reproduction under changes of illumination closely matches that of the target (Wyszecki and Stiles, 1982). A metamerism index is always based on a metric that defines how different two stimuli appear (e.g. CIELAB). To compute the metamerism index between two samples that have identical tristimulus coordinates under a reference illuminant, one chooses a test illuminant. Often the reference illuminant is CIE D65 and the test illuminant is CIE Illuminant A. One then computes or measures the tristimulus coordinates of the two samples under the test illuminant and computes the color difference between these using the chosen color metric. The smaller the difference, the more similarly the two samples appear under the change of illumination. Wyszecki and Stiles (1982) provide discussion and an example calculation.

5.4.2.4 Linear models

Another approach to the problem of metamerism is to specify colors in terms of their physical properties rather than in terms of their tristimulus coordinates. This seems at first like a radical proposal, as it suggests neglecting the economy of specification offered by the color matching experiment. However, as the problem of metamerism itself makes clear, there is sometimes a need to preserve more information about samples than their tristimulus coordinates under a particular illuminant.

A promising theoretical development that might allow such specification is the notion that small-dimensional linear models may be used to describe many surface reflectance functions to a high degree of accuracy. Linear models approximate spectral data as weighted sums of a small number of fixed basis functions (see Chapter 4; Brainard, 1995).

The number of basis functions used in a linear model is called the dimension of the model. This nomenclature emphasizes the fact that basis functions may be interpreted as describing the dimensions along which spectra may vary. The insert in Figure 5.12 shows the basis functions for a three-dimensional linear model for surfaces. The first basis function reflects fairly evenly across the visible spectrum. By varying the weight assigned to this basis function, we can capture variation in overall reflectance from one surface to another. The second basis function reflects positively at the long wavelength end of the spectrum and negatively at the short wavelength end. By assigning a positive weight to this basis function, we capture the fact that some surfaces (e.g. ones that tend to appear red) reflect best at longer wavelengths. By assigning a negative weight to this basis function, on the other hand, we capture the fact that some surfaces (e.g. ones that tend to appear green) reflect best at the middle and short wavelengths. The third basis function, which reflects positively in the middle region of the spectrum and negatively at either end, shows another dimension along which surface reflectances within the model can vary.

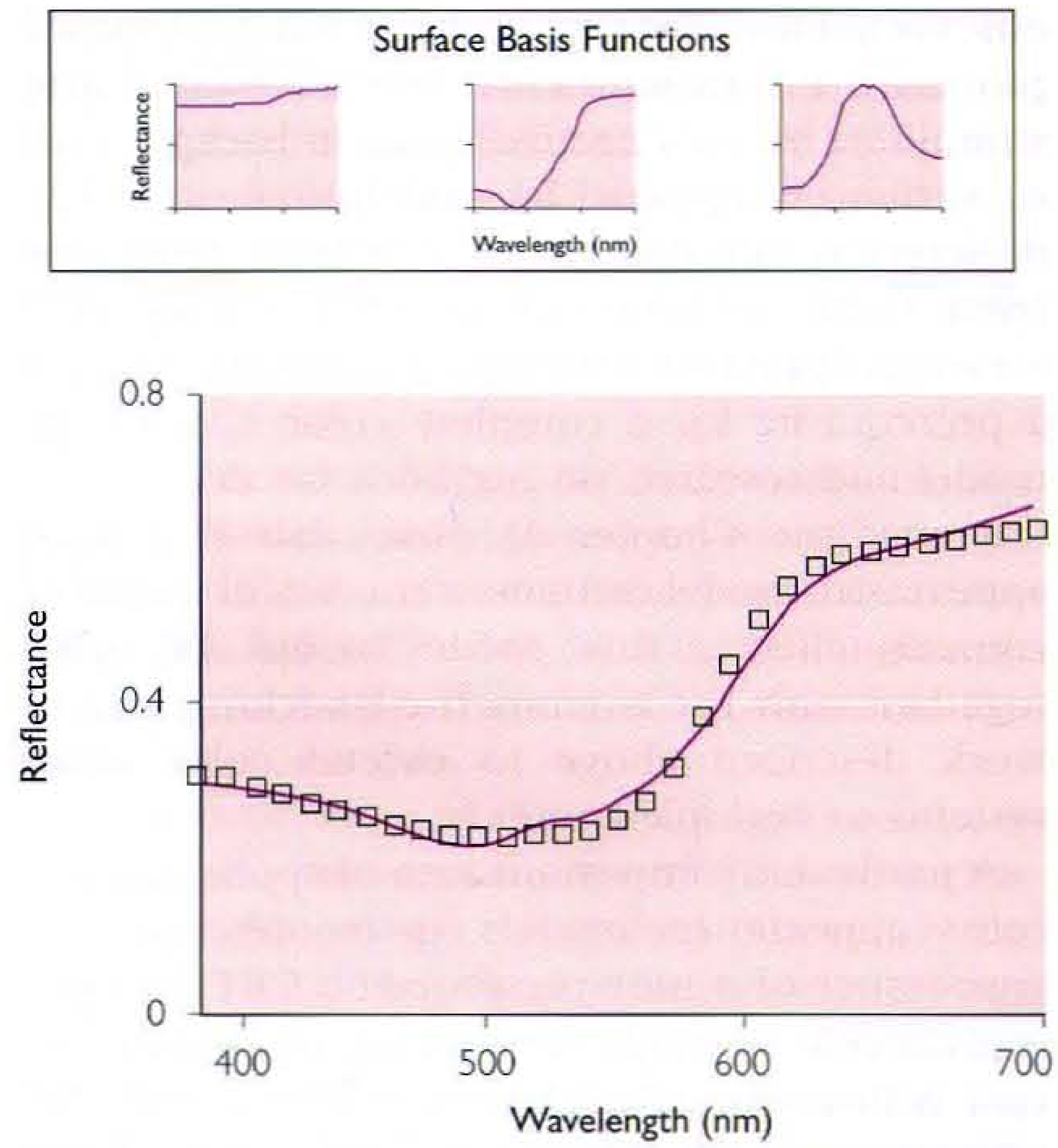


Figure 5.12 **The open squares in the figure show a measured surface reflectance function. The solid line shows an approximation to this function obtained using a three-dimensional linear model. The insert shows the reflectance spectra of the linear model's basis functions. (From Brainard et *al.*, 1993. Copyright © 1993 American Psychological Society, reproduced by permission of Blackwell Publishers.)**

The basis functions shown in Figure 5.12 were obtained by performing a principal components analysis of the reflectance functions of a large set of colored papers (Cohen, 1964). Similar analyses have been performed for other collections of surfaces and for measured daylight spectral power distributions (Judd *et al.*, 1964; Maloney, 1986; Jaaskelainen, Parkkinen, and Toyooka, 1990; Marimont and Wandell, 1992). The results indicate that linear models with a small number of basis functions provide an excellent description of naturally occurring spectra. The main portion of Figure 5.12 shows a typical surface reflectance function and its linear model approximation.

Linear models provide an efficient description for surface reflectance functions, since specifying the weights on each basis function provides enough information to reconstruct a close approximation to the full reflectance function. Brainard and Wandell (Wandell and Brainard, 1989; Brainard and Wandell, 1990) have outlined schemes to incorporate linear model specifications into color reproduction systems. The basic idea as it applies to color order systems is very simple, however. Rather than defining a color order system in terms of the relation between sample tristimulus coordinates and symbolic descriptors, the system could be defined in terms of the relation between linear model weights and the same descriptors. Since it is always possible to compute sample tristimulus coordinates from reflectance spectra (under the standard viewing conditions for which the color order system is defined), the linear model formulation loses no information. The formulation provides extra information, however, since the full spectrum of each sample is available. As methods for accurately controlling sample spectra become available, color order systems using spectral sample specification could provide reproduction whose appearance changes with illumination were well defined. Moreover, with such a scheme, the system's sample spectra might even be designed to have roughly constant appearance across common changes in illumination (Berns *et al.*, 1985).

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NOTES

1 Formulae for the conversion are provided by MacAdam (MacAdam, 1974). The published formulae, however, contain an error. MacAdam's Equation 1 for the computation of $\mathscr{L}$ works only for stimuli with values of $Y_0 > 30$. The formulae published here correct for this problem and work for all values of Y_0. They were inferred by examining Semmelroth (1970) whose Equation 3 provides the basis for MacAdam's Equation 1. The formulae published here were checked by implementing them as MATLAB functions and verifying that they correctly reproduce tabulated values (MacAdam, 1978). The implementation is available as part of the freely distributed Psychophysics Toolbox (http://psychtoolbox.org/, release 2.45 and later). Note also that in addition to propagating the error introduced by MacAdam (1974), the formulae provided in the widely used reference by Wyszecki and Stiles (1982) contain additional errors: they do not incorporate the transformation between $\mathscr{L}$ and L, and the definitions of j and g are reversed.

2 In many applications there is no a priori reason to designate either of the two stimuli being compared as the standard. The effect of arbitrarily choosing one or the other as standard is small as long as small color differences are being evaluated. An alternative is to use the geometric mean of the chroma coordinate: $C^*_{ab\_s} = \sqrt{C^*_{ab\_1} C^*_{ab\_2}}$. This issue is discussed in more detail in the CIE technical report (CIE, 1995).

3 The reference viewing conditions specify, among other things, viewing samples under CIE illuminant D65 against a nonselective background with $L^* = 50$. A complete description of the reference conditions is available in several sources (CIE, 1995; Hung and Berns, 1995; Fairchild, 1998).

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