Chapter 7

Major Color Order Systems and Their Psychophysical Structure

In this chapter only the Munsell, OSA-UCS, and Swedish NCS systems will be discussed. The former two are the most important attempts to create psychologically uniform systems, the latter uses the presumed natural approach of Hering (see Chapter 2) to create a color order system, having a regular structure, but not one uniform in terms of size of perceived differences. There are several other newer color order systems extant, but they neither make claims for uniformity nor for regularity according to new, significant psychological attributes.

The issue of viewing conditions for these systems has been attended to in different ways. As discussed previously, the Munsell system is illustrated as if the chips at each value level would be viewed against an achromatic surround of the same value. Chips of two adjacent value levels are illustrated as if viewed against an achromatic surround of intermediate value. The actual atlas displays the chips on white paper (historically of various degrees of whiteness), thus resulting in distortions of the value scale, particularly at lower values. The OSA-UCS system is defined for an achromatic surround of luminous reflectance $Y = 30$ ($L = 0$). The atlas samples are in transparent jackets. NCS, finally, has been established against an immediate achromatic surround of $Y = 78$ in a light booth painted with an achromatic gray of $Y = 54$. The atlas displays samples on white paper. Both latter systems only result in the intended color experiences when viewed against the appropriate surrounds. Munsell and NCS are defined for

Color Space and Its Divisions: Color Order from Antiquity to the Present, by Rolf G. Kuehni
ISBN 0-471-32670-4

CIE daylight C and the 2° standard observer. OSA-UCS is defined for daylight D65 and the 10° standard observer.

7.1 THE MUNSELL COLOR SYSTEM

Development of the System

Albert H. Munsell was educated as an artist and art instructor. His initial interest in color order (beginning in the 1880s) resulted from the need for an educational tool for instruction in color order for school children and art students as well as a tool for objectively expressing harmonious color relations.[1] His initial concept employed a sphere. The inspiration for the sphere form (Munsell became aware of Runge's book only in 1899) came from a child's ball with colored segments and from plotting the colors of one of his paintings in form of a double spiral, suggesting a sphere (Munsell, 1918). Munsell, having convinced himself that Hering's approach could not be correct, decided to base his hue circle on five primary colors: red, yellow, green, blue, and purple. The main motivation was to be able to express his system in a decimal framework. Munsell, not burdened with detailed knowledge about earlier attempts at systematic color order, unhesitatingly decided to make lightness ("value" in his artistically influenced term) a key attribute. His early sphere models, for which he had received a patent in 1900, placed hues of equal value on the equator, that is, in addition to middle green and red, darkened yellow, and lightened blue and purple. Munsell invented the term "chroma" to designate the radial dimension from the neutral gray center to the equatorial colors. After plotting "intensity" against "luminosity" values of painted pigments, measured by Abney, Munsell realized in the year 1900 that on the basis of attributes hue, value, and chroma, a uniform color solid as represented by available pigments could not fit into a sphere but would form an irregular "spheroid." As a result he abandoned the idea of his color solid fitting into an ideal geometrical solid. Munsell named the irregularly shaped solid a "color tree." He maintained the color sphere as an educational tool until the end of his life, and it remained a part of the descriptive literature of the system until the Second World War (Fig. 7-1). Munsell began preparing an equal value chart of painted paper chips in 1901 and proceeded with charts at other value levels. In 1902 he sketched a model based on constant hue planes and began to assemble corresponding hue charts (Fig. 7-2). During the same years Munsell decided that the system should be visually uniform, that is, steps along the three attributes should, within an attribute, be of equal perceptual size. Having differences of equal perceptual magnitude within all three attributes was contemplated by Munsell but somehow never implemented. In 1904, when preparing a publication describing the system and as part of a patent application, Munsell also had settled on his hue, value, and chroma terminology and color identification scheme. Over a span of five years Munsell had developed all key concepts of the system as they stand today. In 1905 he published his conceptual description of the system

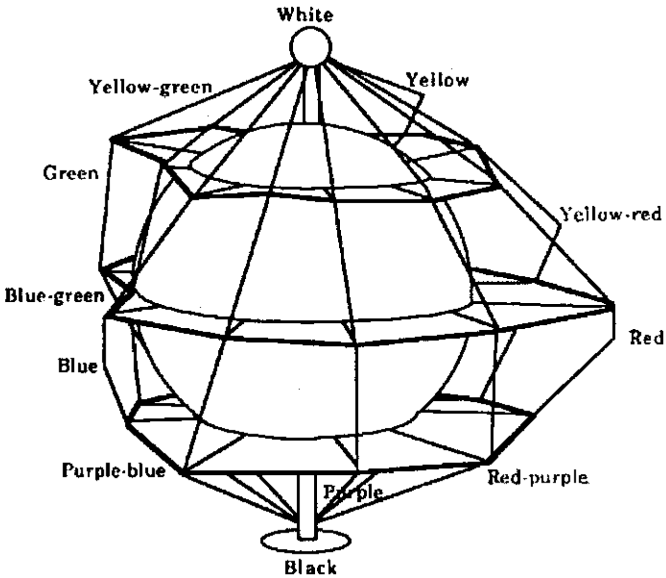

Fig. 7-1 *Munsell's irregular "color tree" enveloping the original sphere. From Derefeldt (1991).*

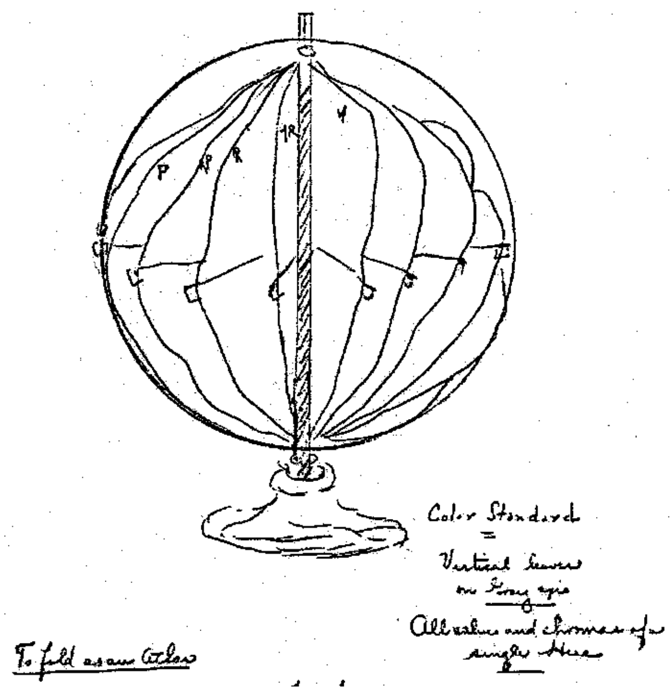

Fig. 7-2 *Trace of Munsell's sketch in his color Diary of an irregular "color tree" with constant hue leafs, dated March 20, 1902.*

under the title *A color notation* (Munsell, 1905). He was granted in 1906 a patent for the system, and he received copyright protection for the charts. In 1907 the first version of the *Atlas of the Munsell color system* was published, containing eight charts with painted samples (Munsell, 1907). A second, enlarged version of the *Atlas* appeared in 1915 (Munsell, 1915). It consists of 15 charts, five constant hue and seven constant value charts, as well as three charts of general descriptive nature.[2]

In the year of Munsell's death, 1918, the Munsell Color Company was formed and continued operating under his son. Scientific support was obtained from the National Bureau of Standards, and the company soon moved from Boston to Baltimore to be closer to the Bureau. One of the young researchers at the Bureau was D. B. Judd. Research on uniform spacing of hue, value, and chroma was continued, and in 1929 the company issued the first version of the *Munsell Book of Color*. The *Munsell Book of Color* is internationally today perhaps the most widely known color order/appearance system and is commercially available in a matte and a glossy chip edition, with a supplementary collection of near-neutral color chips. There is also a textile fabric edition.

The history of the Munsell system has been described by Nickerson (1940, 1969, 1976), Berns and Billmeyer (1985), and Kuehni (2002). A modern description of the system is that by Long and Luke (2001).

The 1915 Atlas

The atlas consists of a text page with four sketches illustrating the color sphere, the color tree, and schematically the position of the vertical and horizontal section charts. The first chart (H) consists of chips of the five primary and the five intermediate hues at values 2 to 8. Chart V consists of the ten-step gray scale and chips of the highest chroma colors of the five primary hues at their appropriate value level. Chart C illustrates chroma scales of the five primary hues shown at their value level. Five charts illustrating vertical cross sections through the solid with always two hues illustrated per chart follow. Finally, there are seven star-shaped horizontal section charts illustrating ten hues at a given value level in all chroma steps possible with the pigments in use.

Fifteen of these chips were measured at the National Bureau of Standards in 1919, and CIE tristimulus values were calculated at a later date. Additional 70 samples were measured in 1926, again with tristimulus values calculated later (Gibson and Nickerson, 1940). When plotted, they do not follow a systematic pattern. Recently measurements of the 58 value 6 color chips of a copy of the 1915 atlas were made by the author. They are illustrated in Fig. 7-3 in the $a^\wedge, b^\wedge$ diagram (fitted to the Munsell Renotations; see equation 7-1 below). The arrangement is reasonably regular. In a few cases the highest chroma level is insufficiently spaced from the previous level. The luminous reflectance values of the samples were found to vary from approximately 36 to 41. Reflectances of the value (gray) scale samples had been measured in 1916 and 1926. The results of the value scale measurements of the 1915 *Atlas* are com-

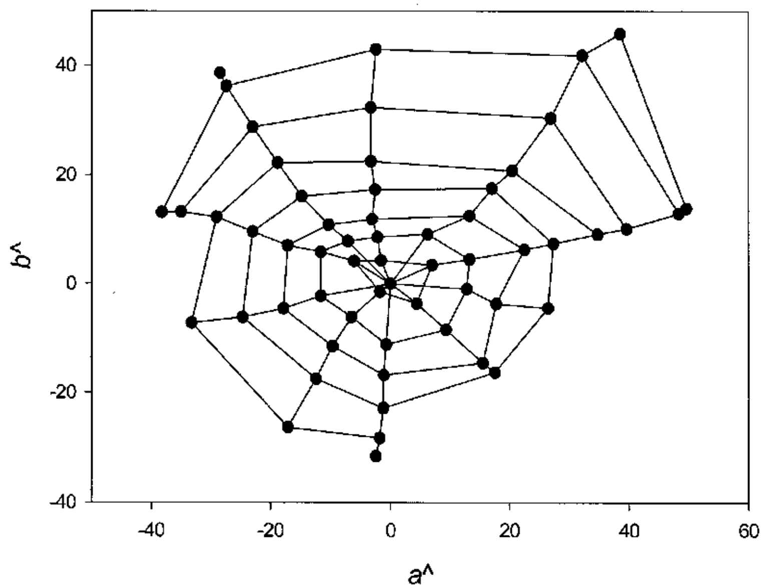

Fig. 7-3 *Location in the* a^, b^ *chromatic diagram of the fifty colors of chart 50 (value 5) of the 1915 Atlas, 2° observer and equal energy illuminant. Radial lines connect colors of constant hue, circular lines colors of constant chroma.*

pared in Fig. 7-4 against measurements of the value samples of the 1929 *Book of Color* (see below). The scales are somewhat uneven and show breaks in continuity: the 1915 *Atlas* value scale between value steps 4 and 5, the *Book of Color* scale between steps 5 and 6. They are indicative of the lightness crispening effect. The 1915 *Atlas* measurements are optimally linearized with a single function by applying a power of 0.43 to the luminous reflectance values.

1929 Book of Color

Based on research conducted together with the National Bureau of Standards, the Munsell Color Company issued in 1929 a revised and extended version of its catalog of sample chips. To distinguish it from the *Atlas*, the new version was called *Munsell Book of Color* (BOC). It consists of twenty hues in values typically from 2 to 8 and chromas from 2 to (in a single case) 14, with a total of 400 samples.

Their reflectances were measured against magnesium oxide in 1935 by J. T. Glenn and J. T. Killian, with MacAdam's help, and the resulting colorimetric data were published in 1940 (Glenn and Killian, 1940). All samples at value 6 have been plotted in Fig. 7-5 in the *a*^, *b*^ diagram. In comparing this figure with Fig. 7-3, we find considerable differences between the two versions, par-

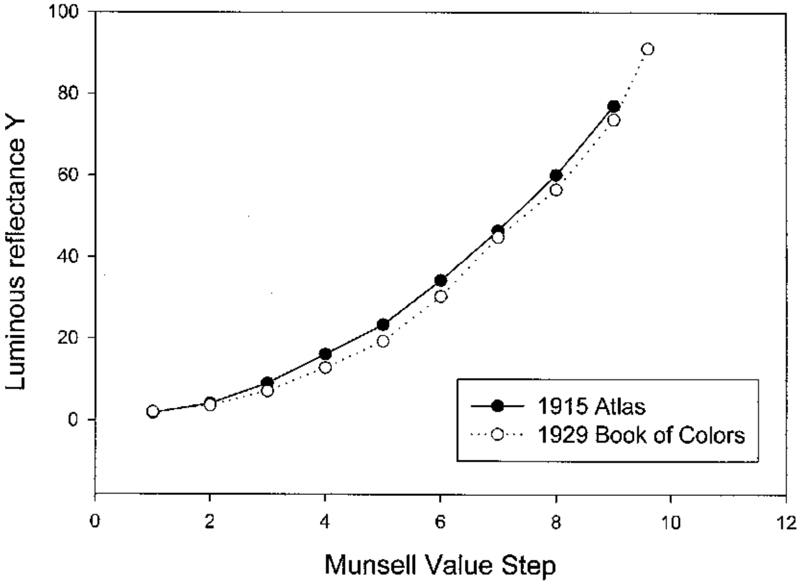

Fig. 7-4 *Luminous reflectance Y of the value scales of the 1915 Munsell* Atlas *(*solid line*) and the 1929* Book of Color *(*dotted line*), 2° observer.*

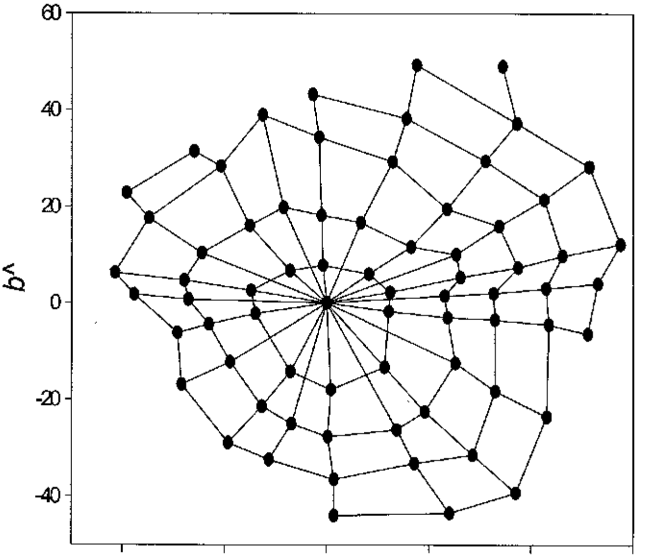

Fig. 7-5 *Location in the* a^, b^ *chromatic diagram of the colors of the value 6 plane of the 1929 Munsell* Book of Color*, 2° observer and equal energy illuminant.*

ticularly in regard to chroma. The luminous reflectances of the value scale of the *Atlas* shown in Fig. 7-4 require, for optimal linearization over the whole range, a power of 0.40 but show evidence of lightness crispening.

The Munsell Renotations

In the mid-1930s the Optical Society of America formed its Subcommittee on the Spacing of Munsell Colors, chaired by Newhall. In 1940 it released a preliminary report describing the psychophysical methods used and preliminary smoothing results for chroma scales (Newhall, 1940). The plotted Glenn and Killian measurements of the 1929 BOC samples and other evidence had indicated jaggedness of constant chroma contours in the CIE chromaticity diagram and, to some extent, of the constant hue lines. In support of the subcommittee's work, 41 subjects had made estimates of the magnitude of differences between gray scale chips of the 1929 BOC to be used for a redefinition of the value scale. All visual estimates were made against a white, a midgray, and a black background (see Fig. 5-16). The report lists averages and ranges of the judgments. A significant and systematic effect of the surround on value judgments was noted. A change in continuity of the value function indicative of the lightness crispening effect in both the ΔR versus R function (where R is luminous reflectance) determined by just noticeable difference measurement and R versus value function from consecutive halving of the scale had also been reported by Munsell et al. (1933), as mentioned in Chapter 5.

In 1943 the committee released its final report (Newhall et al., 1943). Minor irregularities in the mean revised experimental spacing results were smoothed in the CIE chromaticity diagram. The lightness crispening effect in the value scale against the gray surround was also smoothed away. Trends in hue and chroma were extrapolated to the object color limits of the x, y, Y psychophysical color space. The resulting *Renotations*, expressed for the CIE 2° observer and illuminant C, define aim values for 2746 chromatic and nine achromatic colors. Approximately 65% of these have been physically realized as color chips in two volumes of the BOC. The committee used Judd's definition of the value function in form of a smooth quintic equation relating value to luminous reflectance (see equation 5-8). The Munsell Renotation data have also been published in Wyszecki and Stiles (1982).

Aim colors at every second of the 40 defined hues of the Renotations (5 and 10) up to chroma 14 at value 6 are plotted in Fig. 7-6 in the $a^\wedge$, $b^\wedge$ diagram. The changes compared to the 1915 *Atlas* and the 1929 BOC are clearly apparent.

A software package (Leonardo 2000) has been released containing reflectance functions for the Renotation colors achievable with pigments. It allows the calculation of colorimetric aim points for both standard observers and any defined illuminant. It has a display facility that reproduces on the monitor any such generated Munsell aim color (Brill et al., 2001).

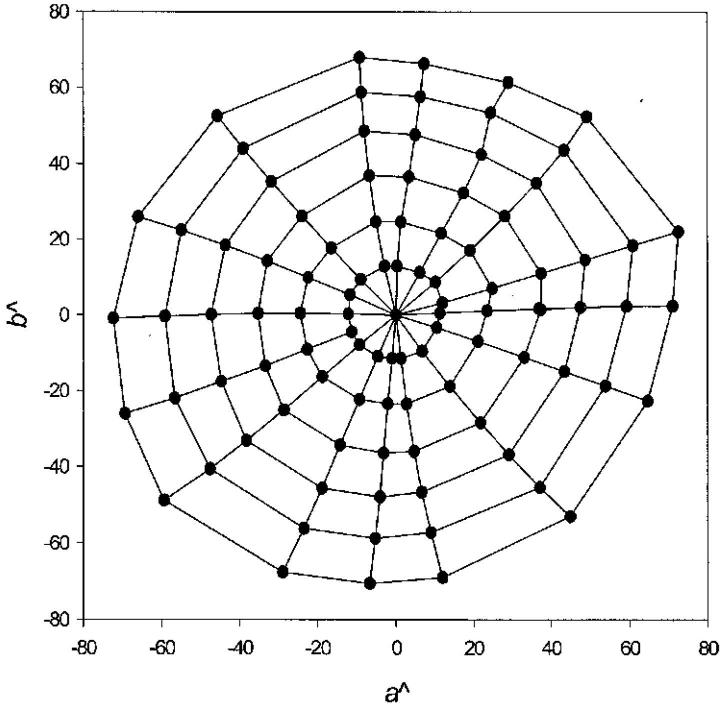

Fig. 7-6 *Munsell Renotation aim colors for the 2° observer and equal energy illuminant. Every second hue (5 and 10) at value 6 and chroma 0–12 in the* a^, b^ *chromatic diagram. Compare with Figs. 6-30 and 6-31.*

The Munsell Re-renotations

During the 1950s and 1960s the Committee on Uniform Color Scales of the Optical Society of America, under the leadership of Judd, conducted a series of experiments with the goal of developing an improved uniform color solid and associated space formula. Judd summarized these experiments in four reports (Judd, 1955, 1957, 1965, 1967). Judd and Nickerson were interested in the impact of the results of these experiments on the Munsell system. As discussed below, the committee pursued a different path, ultimately resulting in the Society's *Uniform Color Scales*. In 1967 Judd and Nickerson published a National Bureau of Standards report in which they proposed revised Renotations that reflected the new experimental findings. They specified a total of 2874 chromatic colors, in a complete revision of the Munsell system (Judd and Nickerson, 1967). Even though only a small number of corresponding samples were produced for experimental purposes, it is instructive to review the *Re-renotations* to gain insight into the work of the committee. The same aim colors (by name) of the Renotations used for Fig. 7-6 are illustrated for the Re-renotations in Fig. 7-7. It is evident that they represent a significant change.

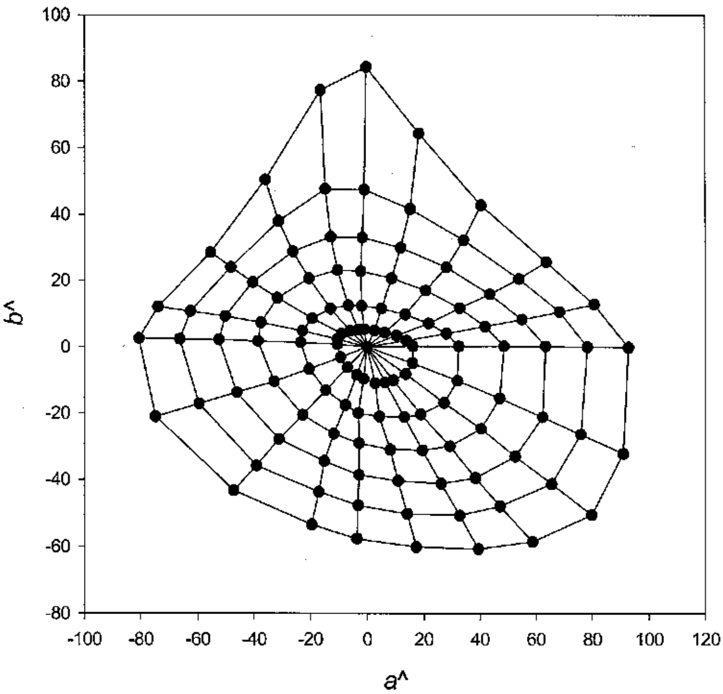

Fig. 7-7 Munsell Re-renotation aim colors for the 2° observer and equal energy illuminant. Every second hue (5 and 10) at value 6 and chroma 0–12 in the a^, b^ *chromatic diagram. Compare with the Renotation colors of Fig. 7-6.*

Munsell Psychological Space and Psychophysical Representation

As already sketched in Chapter 2, the ideal form of the Munsell system is cylindrical with a uniformly spaced hue circle, chroma, and value scale. We have seen earlier that this form does not account for the superimportance of hue nor for the irregular distribution of unique hues. It also is not uniform in hue terms in that the hue difference between two adjacent planes of constant hue at constant lightness varies as a function of chroma but not in the way the constant hue angle between the two planes indicates (see below). A conceptual view of the Munsell system is shown in Fig. 7-8. From the discussion above it is evident that this figure is inaccurate in regard to hue difference in terms of the basic goals of uniformity of difference, at least within an attribute. To project the reflectance functions into a space in such a way that the cylindrical form of Fig. 7-8 is duplicated has been a long-standing goal. Many attempts have been made since the definition of the Munsell Renotations, as has been seen in Chapter 6. The more successful ones are based on a form of opponent color system. Such systems usually make use of the CIE colorimetric system, the best-known example being the CIELAB color space formula. The CIELAB formula is not a very good representation of the Munsell

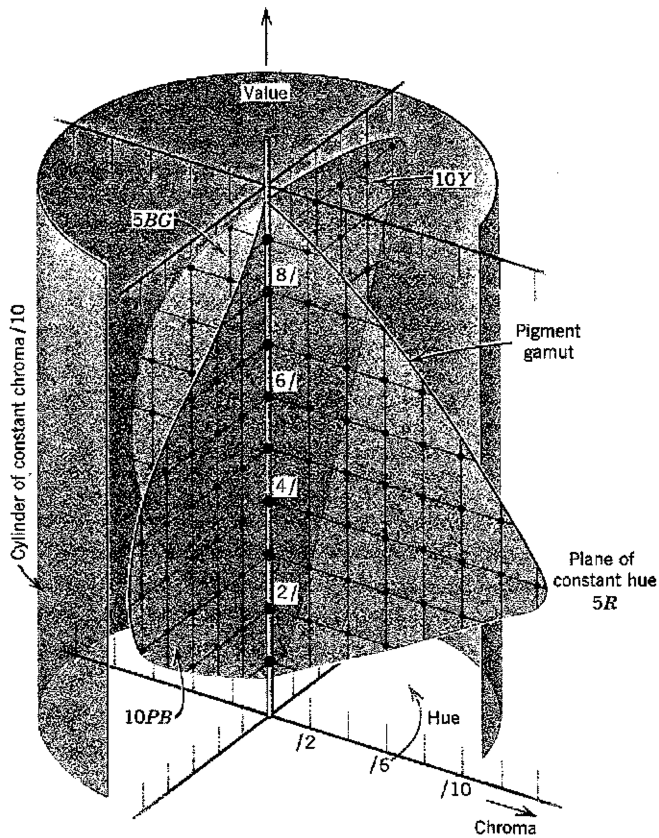

Fig. 7-8 Schematic view of the cylindrical organization of the Munsell system, illustrating four constant hue planes and the organization of samples on these planes. The chromatic plane is not representative of the perceptual relations in the Munsell system. From Judd and Wyszecki (1975).

psychological space as illustrated in Fig. 7-9 for the colors of Fig. 7-6. Among other things, it also has the same weakness in regard to hue difference as the psychological conceptual system of Fig. 7-8.

Among the assumptions implicit in most psychophysical models are: (1) colors are defined by two opponent color coordinates *a* and *b* and luminous reflectance and (2) unit color difference contours can be expressed in terms of distances in *a* and *b*. The CIELAB formula makes the additional assumption that the power modulation of the tristimulus values used to calculate a^*, b^*, and L^* is uniform and its value is cube root. As discussed before, this assumption was made by Adams in 1942 and is still in use. The b^* axis resulting from application of the 2° observer is a reasonable representation of unique yellow and blue, but as we have seen, the a^* axis does not coincide with unique green and unique red. Disregarding this difficulty, we can take the

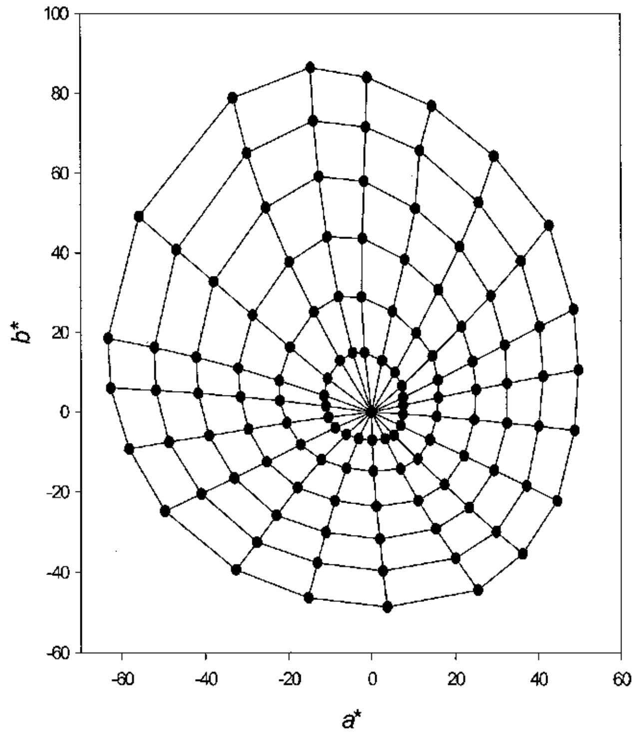

Fig. 7-9 Representation of the colors of Fig. 7-6 in the CIELAB a*, b* *diagram, 2° observer and equal energy illuminant.*

a^* scale to approximately represent greenness-redness and the b^* scale yellowness-blueness. In the four quadrants of the a^*, b^* diagram the number and spacing of hue difference steps of equal size varies.

The power modulation implicit in the Renotations can be investigated by checking it along the axes. Because adaptation negates most of the effect of different broadband white light illuminants, tristimulus values are, for purposes of simplification, normalized to the equal energy illuminant. By definition, colors along the chromatic axes at constant luminous reflectance change in X, respectively Z, only. When plotting these values, we find that the power modulation required to optimally linearize the progression of tristimulus values of the corresponding nearest Renotation colors differs by semi axis (Kuehni, 2000b). In Fig. 7-10*a* and *b* the progression of X, respectively Z, values of Munsell Renotation colors at value 6 along or very near to the opponent axes is illustrated as a function of chroma. The results indicate discontinuous functions, separated by the neutral gray. The optimized power functions for the four segments are as follows (as shown in Table 5-2): $a-$ (green) colors 0.19, $a+$ (red) colors 0.15, $b-$ (blue) colors: 0.06, $b+$ (yellow) colors 0.42. All are significantly different from a cube root function. The equations used for

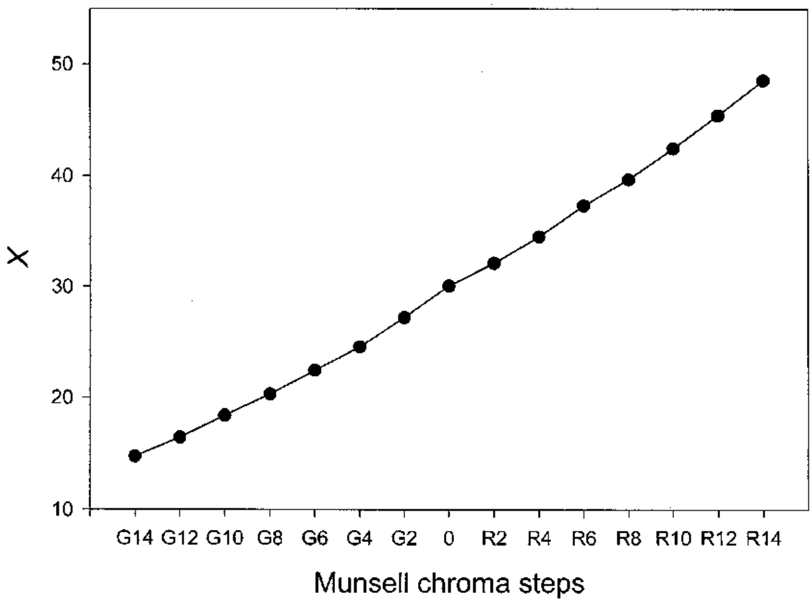

Fig. 7-10a *Progression of* X *tristimulus values of Munsell colors nearest to the* a *opponent color axis as a function of Munsell chroma, value 6, 2° observer, and equal energy illuminant.*

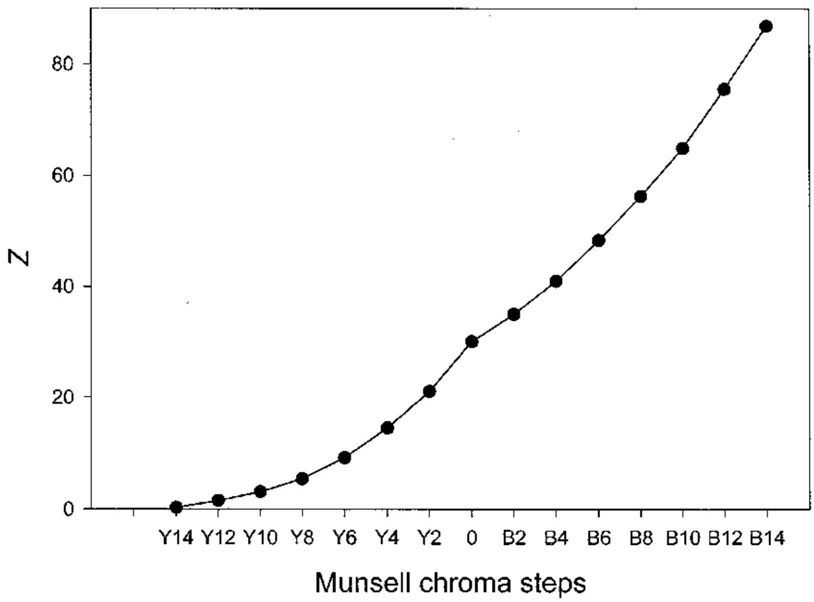

Fig. 7-10b *Progression of* Z *tristimulus values of Munsell colors nearest to the* b *opponent color axis as a function of Munsell chroma, value 6, 2° observer, and equal energy illuminant.*

calculating the chromatic coordinates of the colors of Figs. 7-3, 7-5, 7-6, and 7-7 are as follows:

$$a^\wedge+ = 3500\left[\left(\frac{X}{X_0}\right)^{0.15} * \left(\frac{Y}{Y_0}\right)^{0.85} - \left(\frac{Y}{Y_0}\right)\right],$$

$$a^\wedge- = 2000\left[\left(\frac{X}{X_0}\right)^{0.19} * \left(\frac{Y}{Y_0}\right)^{0.81} - \left(\frac{Y}{Y_0}\right)\right],$$

$$b^\wedge+ = 1400\left[\left(\frac{Y}{Y_0}\right) - \left(\frac{Z}{Z_0}\right)^{0.06} * \left(\frac{Y}{Y_0}\right)^{0.94}\right],$$

$$b^\wedge- = 485\left[\left(\frac{Y}{Y_0}\right) - \left(\frac{Z}{Z_0}\right)^{0.42} * \left(\frac{Y}{Y_0}\right)^{0.58}\right], \qquad (7\text{-}1)$$

where X, Y, Z are the CIE tristimulus values of the Munsell colors for the 2° observer and illuminant C and X_0, Y_0, Z_0 are the tristimulus values of illuminant C. The resulting $a^\wedge$ and $b^\wedge$ values are on average of the same size as those obtained with the CIELAB formula. Without a further, nonlinear scaling factor the formula is only applicable to value 6.

From the Cone Shape in Tristimulus Space to the Cylinder in "Uniform" Psychophysical Space

As was seen in Chapter 5, constant chroma circles at different value levels approximately form an inverted, slanted cone in *X*, *Y*, *Z* tristimulus space. When translated into the linear opponent color space, an inverted cone remains but is aligned with the vertical *Y* dimension of *a*, *b*, *Y* space. Conceptually application of a constant power to tristimulus values efficiently converts this cone into a cylinder. When plotting Munsell Renotation colors closest to the *b* axis of the opponent color space (close to unique yellow and blue for the average observer) colors of the same chroma at different value levels are found to fall on a straight line (at higher values) that turns into a curved line at lower values (Fig. 7-11*a*). The same applies to colors closest to the *a* axis (Fig. 7-11*b*). However, the pattern is different. Much less of the available area is filled by the bluish green-to-bluish red colors than by the yellow-to-blue colors. When extrapolating the initially straight lines they are found not to intersect in one point. Intersection in one point applies if the chroma spacing at a given level of value is linearized by the same power as the value scale. But as we have seen, the chroma scales in the four axis directions from the central gray colors are optimally linearized by different powers. The Munsell Renotations have curiously uneven first steps from gray in the four directions. The validity of these steps could not be confirmed (Kuehni 2000c). Figure 7-11*a* and *b* indicate the constraints on the existence of certain colors at certain value levels.

Figure 7-12 illustrates the Weber fractions of *Z* at various value levels. The surprising result is two nonlinear functions of mixed composition, the upper

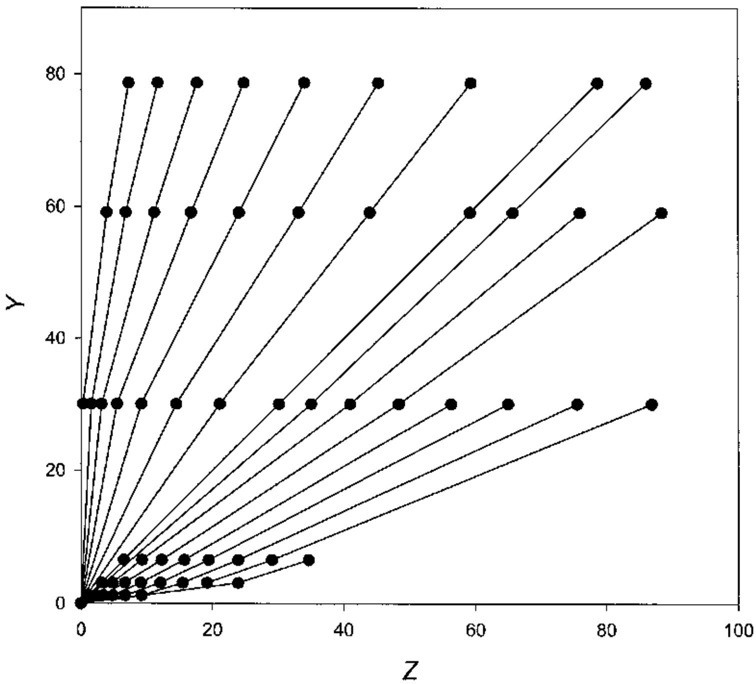

Fig. 7-11a *Plot of Munsell colors nearest to the* a *axis at six value levels (from the top 9, 8, 6, 3, 2, 1) in the* X, Y *diagram, 2° observer and equal energy illuminant. Colors of constant chroma at different value levels are connected by lines.*

consisting primarily of higher value colors and the left half of the lower curve of lower-value colors. As a result of the different powers required for chroma linearization, a cylinder is not obtained without additional adjustment. Empirically the application of a factor of $0.133Y^{0.59}$ was found to provide the required correction for the Renotations (Kuehni, 1999).

Curvature of Constant Hue Lines in the CIE Chromaticity Diagram

In most cases Renotation colors of constant hue are found to fall on curved lines in the CIE chromaticity diagram (Fig. 7-13). This is the result of the so-called Abney effect (Abney, 1910). When varying amounts of an achromatic light are added to a monochromatic light the resulting hue is not constant but changes as a function of the relative contents of chromatic and achromatic light. When such lights or corresponding object colors are represented in a uniform chromatic diagram constant hue lines become straight. Mathematical/geometrical relationship between the two methods of presentation provides an explanation. In a conceptual example an *a*^, *b*^ diagram is illustrated (Fig. 7-14*a*) in which the colors along the four axes required different powers

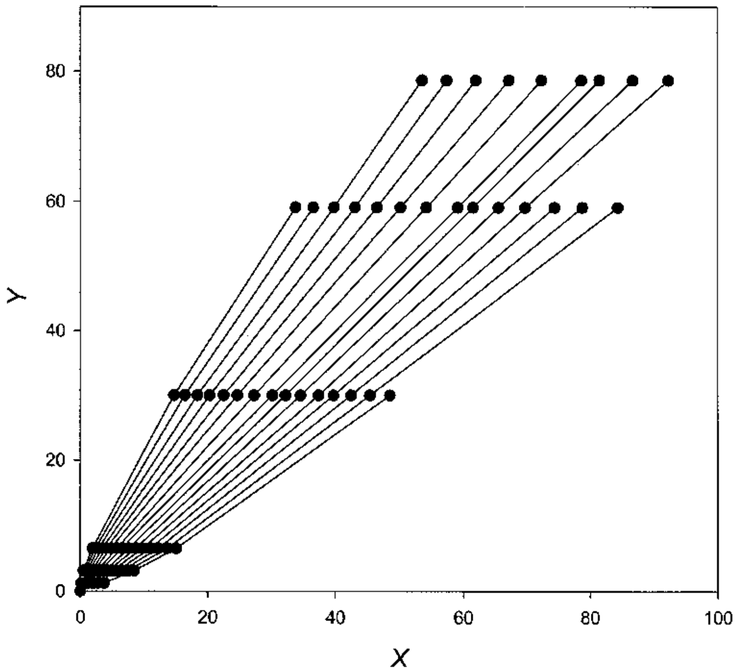

Fig. 7-11b Plot of Munsell colors nearest to the b axis at six value levels (from the top 9, 8, 6, 3, 2, 1) in the Z, Y diagram, 2° observer and equal energy illuminant. Colors of constant chroma at different value levels are connected by lines.

for optimization (a^+: power 0.75, a^–: power 0.5, b^+: power 0.25, b^–: power 0.333).

Calculating backward to a linear a, b diagram (Fig. 7-14b), we find the axis colors spaced differently and the intermediate colors connected with lines of different curvature. Curvature of the lines of intermediate color is also obtained if the colors along an axis are optimally linearized by a single power. If the same power is required for both axes, the line at 45° is straight while the one at 135° has a curvature. When calculating the corresponding chromaticity coordinates (Fig.7-14c) curvature is also obtained. Geometry requires that in order to have straight lines after linearization with the appropriate power non-axis lines need to be curved both in the linear a, b and the x, y diagrams in a way that depends on the powers involved. Thus in the x, y diagram most lines connecting constant hue colors of the Renotations are curved.

Unit Difference Contours in the Munsell System

Given the information about the relative magnitude of hue, value, and chroma differences in the Munsell system by Nickerson and by Bellamy and Newhall

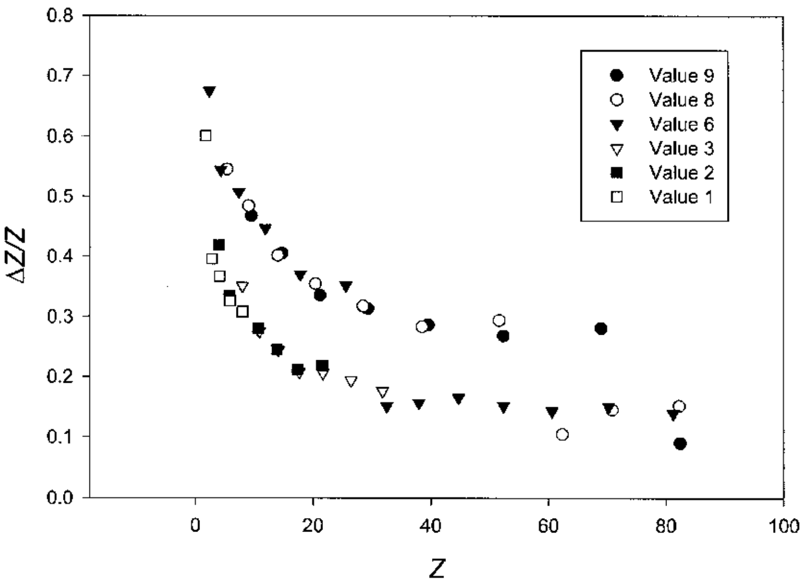

Fig. 7-12 Weber fractions ΔZ/Z as a function of tristimulus value Z *of Munsell colors nearest to the* b *axis at six value levels, 2° observer and equal energy illuminant.*

and that colors falling on two neighboring constant hue lines vary in hue differences between them, we can make estimates of the shape of unit chromatic differences in the Munsell system. At the level of differences of the magnitude of Munsell chroma steps, at chroma 5 three Munsell 100 hue steps equal two chroma steps. On this basis most unit contours in the psychological diagram are of a rectangular or oval nature (or perhaps trapezoidal) with the major axis of the contours aligned with constant hue lines. Based on Nickerson's relationship at chroma 5 we can calculate a ratio between major and minor axis of approximately 2:1. Using the ratio of Bellamy and Newhall at threshold the ratio is approximately 2.8:1. This indicates that unit contours at Munsell sample size differences are somewhat less elongated than at threshold level, that is, smaller hue differences require a relatively smaller stimulus increment than larger hue differences. Judd showed in 1968 that, as a result of the unit difference contour, a uniform perceptual color space cannot be mapped isomorphically into a geometric space. A euclidean model of a uniform space at the level of Munsell differences is impossible. Judd's answer to this question was a "crinkled fan" (Fig. 7-15). While a sector of this fan can be spread out a complete circular crinkled fan cannot. As a result it is apparent that the Munsell system is but a regular approximation of a uniform color solid.

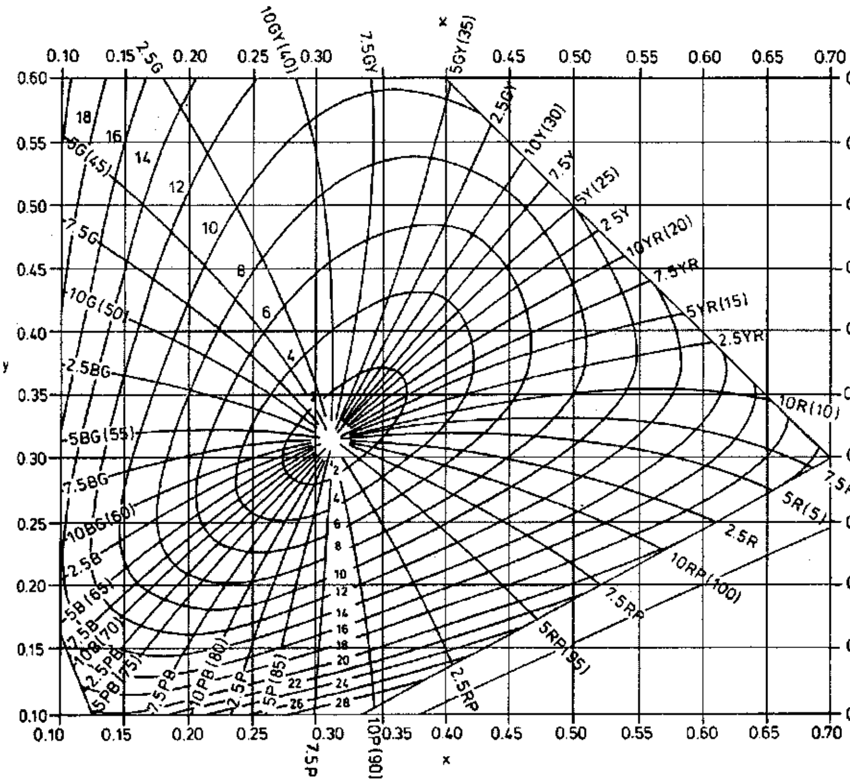

Fig. 7-13 *Portion of the CIE chromaticity diagram with radial lines of constant Munsell hue and ovals of constant chroma, 2° observer and illuminant C. From Agoston (1987).*

7.2 OPTICAL SOCIETY OF AMERICA UNIFORM COLOR SCALES (OSA-UCS)

Development of the System

We have already encountered some aspects of the development of OSA-UCS in the discussion of the Munsell Re-renotations. In the 1940s the issue of a uniform color space had the attention of the American National Research Council and a list of industries and governmental departments that could profit from the outcome had been established (Judd, 1955). In 1947 the Optical Society of America decided to undertake this research and a committee under the chairmanship of Judd (at the National Bureau of Standards) was appointed. He chaired it until shortly before his death in 1972 whereupon MacAdam assumed chairmanship. Membership varied somewhat during the nearly 30 years of its existence but never consisted of more than fifteen people (Nickerson, 1977). Based on a paper from 1941 by Balinkin, describing regular

Fig. 7-14a *Hypothetical colors falling on the axis lines and intermediate angles in an* a^, b^ *diagram that by semi axis required different powers for linearization.*

Fig. 7-14b *Back-calculated linear opponent color diagram of the same colors showing curvature of lines connecting intermediate angle colors.*

tetrahedral tiling of a uniform color space, Foss made already in the first formal meeting of the committee in 1947 a proposal to tile the committee color space in this manner. As L. Silberstein had pointed out in 1942, if one makes the size of color differences in a triangle equal in magnitude, there can only be six nearest neighbors in the chromatic plane for the system to be euclidean. With more than six neighbors the space assumes hyperbolic shape, with less than six Riemannian. Silberstein recommended testing hexagonal arrays of colors

Publisher's Note:
Permission to reproduce this image online was not granted by the copyright holder. Readers are kindly asked to refer to the printed version of this chapter.

Fig. 7-14c *Colors from Fig. 7-14a in the CIE chromaticity diagram showing a different curvature of intermediate angle color lines.*

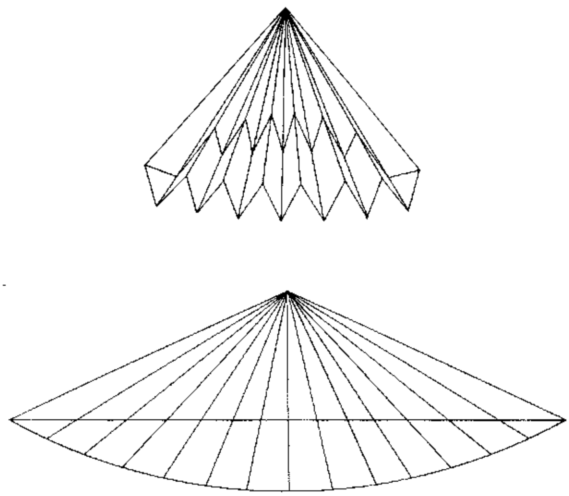

Fig. 7-15 *Segment of Judd's "crinkled fan" uniform color difference surface which considers the unit uniform difference contour of the Munsell system as a ratio between major and minor axes of 2:1. The straight line across the open fan is a secant. It is also shown on the crinkled version. When the crinkled fan is circular (representative of the total Munsell hue circle), it cannot be spread out (Judd, 1968).*

to determine if color space is euclidean. As we will see, in its experimental work the committee decided to follow this recommendation.

At the time there were three schools of thought in the committee:

1. The experimental facts of color difference are established, and no further work in this respect is required.
2. The experimental facts are very complex and appear to prove that a uniform euclidean color space is not possible. The best goal of the committee is to develop a simple color difference formula.
3. Uniformity, or its lack, is best exemplified by a set of color chips.

As it progressed the committee developed new experimental data, found that a uniform euclidean space is not possible, and developed what it considered to be the best approximation of a uniform euclidean system possible, exemplified by a set of chips and a formula.[3]

By the end of 1954, 38 color studies related to uniform color scaling had been reviewed (Judd, 1955). In 1952 a decision was made to assemble a 500-chip uniform three-dimensional sample set in a regular rhombohedral arrangement based on the Munsell Renotations, adjusted for its discrepancies with the results of the MacAdam (1942) and Brown-MacAdam (1949) color-matching error data. In preparation Nickerson, Judd, and Nimeroff in 1955–56 developed a constant saturation locus at value 6 (see Fig. 5-22). Newhall determined hue spacing on this locus in 1957–58, and Howett determined chromaticness spacing for near grays at values 3, 6, and 8 as well as chromaticness spacing of the Munsell value 6 plane.

Following Silberstein's recommendation, a color scaling experiment involving 43 color samples at near-constant luminous reflectance in a triangular grid pattern was then undertaken. Two auxiliary experiments were also performed: (1) determination of the relative size of chroma steps at value 6 to value steps at the same value level; (2) determination of the value of the gray having the same perceived lightness as the 43 samples with nominal value 6 (test of the Helmholtz-Kohlrausch effect). The 43 samples were arranged to form contiguous triangles in the chromatic plane, none involving the achromatic gray (Fig. 7-16). They are fundamental for the subsequent development of the Uniform Color Scales. From this arrangement 107 (mixed hue and chroma) differences between nearby colors resulted. They were evaluated by a total of 76 observers (different portions of the total set by different numbers of observers and under presumably somewhat different viewing conditions) in a two-category forced choice experimental paradigm where the observers determined if the difference between given samples A and B was larger or smaller than the difference between samples B and C.[4] From the results psychometric scale values were calculated at the NBS. The scale values were evaluated against four color difference formulas: CIE U*V*W*, Glasser-Reilly cube root, Munsell Renotation (modified Nickerson Index of Fading), and MacAdam-Friele 1965 (see Chapter 6). The highest correlation coefficient

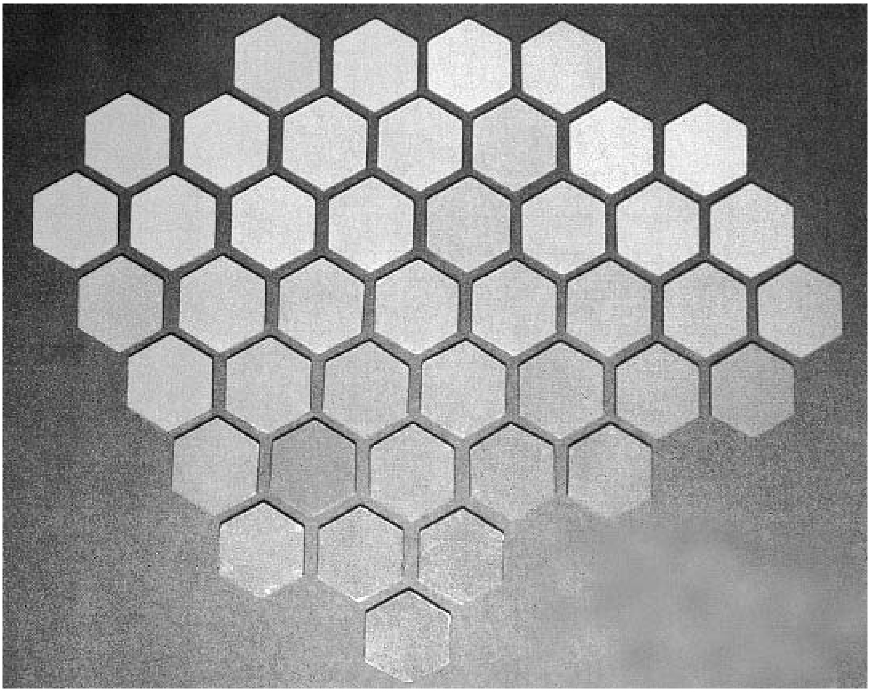

Fig. 7-16 *Image of the 43 hexagonal enamel color plates used by the OSA-UCS committee to establish the fundamental perceptual data for the system. Note that there is no achromatic color among them. (See color plate.)*

between visual and calculated color differences was a disappointing 0.45 and was achieved with the Munsell formula. A series of iterative steps (12 revisions, 33 steps) was subsequently taken to modify that formula as well as the Munsell Renotation aim data to improve the correlation between formula and committee data to 0.80. The resulting revised aim data are the Re-renotations of the NBS report discussed above.

Reilly developed modifications of the cube root formula to improve correlation with the visual data, and MacAdam proceeded from the MacAdam-Friele space to a nonlinear transformation space based on geodesics. Reilly found that correlation was significantly improved by applying a superhue weight of 2.3. Key results obtained from analysis of the visual data and comparison with colorimetric data were as follows:

1. Additivity fails by as much as 30%: ratio judgments of the differences between neutral gray and constant chroma chromatic colors in opposite direction found them to be larger by up to 30% than the direct difference between the two terminal colors.
2. Psychometric scales were found to be nonlinearly related (power 0.37 to 0.80) to *chromaticity coordinate* differences.

It had become evident that it was impossible to present the results of the evaluation of the 43 samples of the value 6 plane on a flat surface. Thus the results were in this respect in agreement with the Munsell system and findings of the MacAdam color-matching error data. The committee decided to proceed along two lines:

1. Prepare a set of color chips representing the closest a euclidean system can come to a uniform color solid and thereby to demonstrate "the reality of the various geometrical difficulties embodied in a set of painted colors" (Nickerson, 1977).
2. Develop a euclidean mathematical formula that best describes the experimental findings. At its thirteenth meeting in 1967 the committee voted to adopt the following statement: "We will affirm to the world that no regular rhombohedral lattice sampling of color space, with a fixed background, can exist; we will produce the best approximation to such a lattice for neutral value 6 background that we can design; and we will specify some or all of the perceived sizes of the differences in our lattice."

The interest of design-oriented people in the novel scales revealed by the crystalline structure was also a consideration for continuing the effort.

The test of the magnitude of the Helmholtz-Kohlrausch effect using a set of gray tiles to compare against the 43 chromatic tiles gave results in reasonable agreement with the Sanders and Wyszecki (1957) determination using light colors (see Chapter 5 for a quantitative comparison of the two sets of data). The committee developed a formula to describe the results as a function of the CIE chromaticity coordinates.

To establish additional experimental facts of the relationship between chromatic and lightness differences, another four sets of four samples each were prepared. Each set formed a regular tetrahedron in the tentative "uniform" color space, one set being yellow at $Y = 90$, another red at $Y = 10$, the third green at $Y = 30$, and the last blue at $Y = 6.6$. Differences were compared within and across sets. A table with the final data lists the observed scale differences as determined from the psychometric scales, the difference computed with the committee's formula and the error (MacAdam, 1974).

Optimized Formula

With the visual results in hand several independent efforts to arrive at an optimized mathematical formula were made. In 1970 two formulas were in contention as the best: a version of MacAdam's nonlinear transformation formula (xi, eta formula; see Chapter 6) and Reilly's modified cube root formula. MacAdam's formula was found not to extrapolate well beyond the experimental data. The committee was interested in a formula that extends reasonably to the limits of object color perception (the MacAdam limits). Reilly's formula was found to do a better job in this respect. Various parameters of

Reilly's formula were now optimized to provide the best correlation obtainable with such a formula (see equation 6-54). The committee selected a set of color fundamentals *R*, *G*, *B* to fit the visual data that imply as yet unknown neurophysiological processes to achieve the fit, illustrated in Fig. 7-17*a*. Figure 7-17*b* shows the committee's opponent color functions *j* and *g*. In Fig. 7-17*c* the linear form of these functions is compared to balanced linear opponent functions *a* and *b* derived from the 10° observer functions. For ease of comparison the conventional functions have been multiplied by a factor of 8. The results indicate systematic deviations, particularly in higher implied redness and lower blueness of bluish-reddish colors (short wavelengths).

The lightness scale is a modified Semmelroth scale based on a surround of $Y = 30$ and is illustrated in Fig. 7-18. Lightnesses of chromatic colors are further adjusted by a correction for the Helmholtz-Kohlrausch effect in the form of a modified Sanders-Wyszecki formula with calculation from CIE chromaticity coordinates (it should be noted that experimental determination of the HKE had been made only at one level of luminous reflectance).

The fit of the formula to the visual data involving 43 samples is shown graphically in Fig. 7-19 (MacAdam, 1974). The gaps represent cases where the calculated difference exceeds the average perceived differences, and the rectangles the opposite. It is evident that while there is a general impression of inhomogeneity, there is a degree of systematic deviation. Individual differences have errors of the calculated difference of up to 70%. For a mean observed difference of 2.483 units for all 174 differences included by the committee the root mean square error (RMS) using the committee's final formula

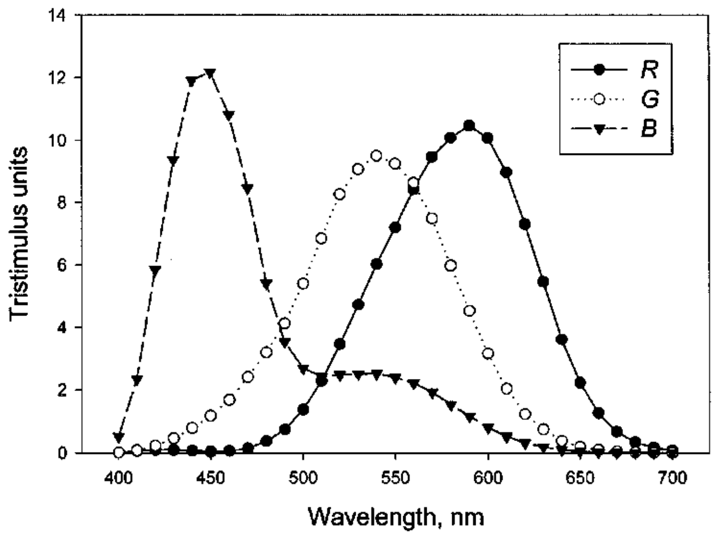

Fig. 7-17a *Spectral* R, G, B *functions selected by the Committee on Uniform Color Scales for the formula fitted to the experimental data, 10° observer and illuminant D65.*

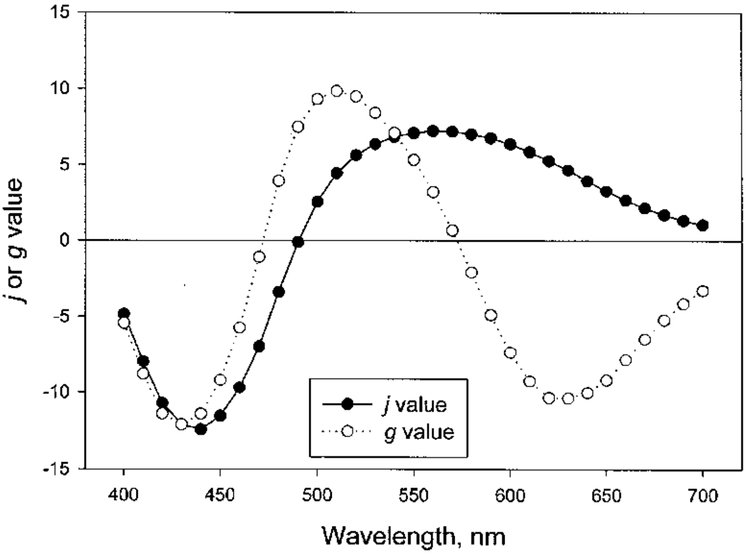

Fig. 7-17b *Spectral opponent color functions* j *and* g *as defined by the Committee, 10° observer and illuminant D65.*

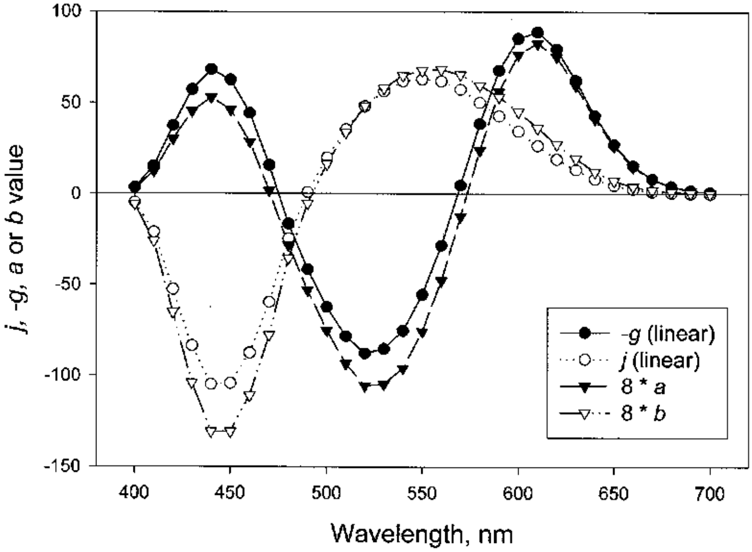

Fig. 7-17c *Comparison of linear spectral opponent functions of the OSA-UCS system with balanced linear functions* a *and* b *derived from 10° observer data. For ease of comparison the linear* g *function has been inverted and the* a *and* b *functions multiplied with the factor 8.*

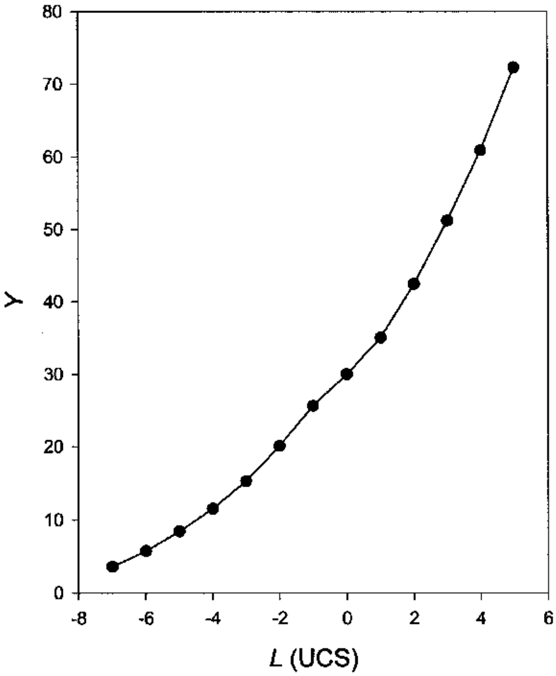

Fig. 7-18 *OSA-UCS lightness* L *as a function of luminous reflectance* Y*, with lightness crispening for surround* L *= 0.*

was calculated as 0.421, or 17%. The correlation coefficient between calculated and observed values is 0.45.

The system was described by MacAdam in 1974. An extensive report of the work of the committee, envisaged by Judd, was never published. It is surprising to note that the issue of hue superimportance and its implication for the accuracy of OSA-UCS is absent from the system description. Judd covered hue superimportance in considerable detail in his 1968 paper on ideal color space but without reference to OSA-UCS. In his book *Color measurement* of 1981 MacAdam made the following statement: ". . . the committee forced the data into a euclidean form, despite clear indications that the judgment data required noneuclidean representation." The issue is absent in Wyszecki and Stiles's, Derefeldt's, or Berns's recent description of OSA-UCS (Berns, 2000).

OSA-UCS Atlas

With the formula established, the committee proceeded to sample the implied space according to the rules of regular rhombohedral sampling. Rather than use triangular sampling of the constant lightness plane, it was decided to rotate the unit cubo octahedron to obtain a square grid in the constant lightness

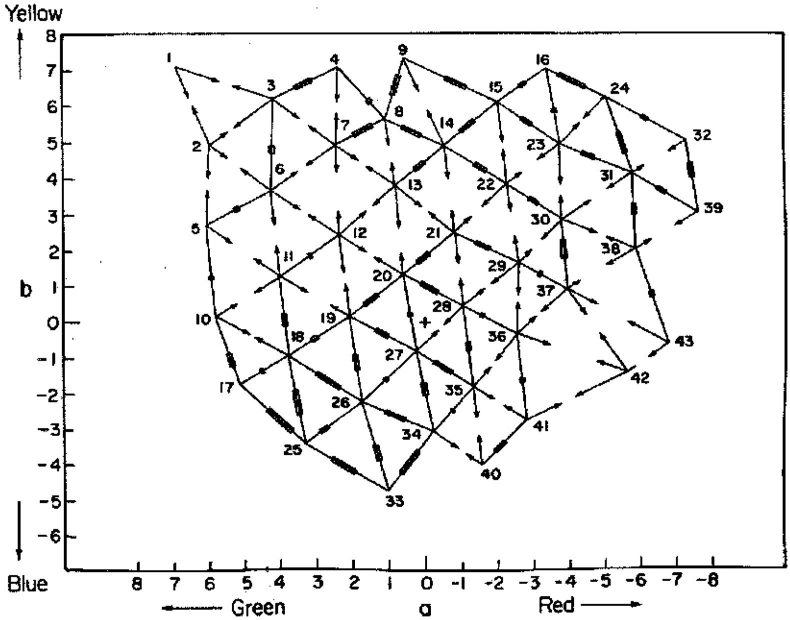

Fig. 7-19 *Plot of 102 chromatic differences between 43 color samples in the chromatic diagram of the Committee on Uniform Color Scales. Numbers identify the samples. Lines with arrows and bars indicate the size of the average visual judgments. The colorimetric difference is too small in case of arrows, too large in case of bars. From MacAdam (1974).*

plane. The twelve distances from the central point M to any of the points on the surface of the cubo octahedron are the same (Fig. 7-20; see also Figs. 2-49 and 2-50). By implication, the distances between the four points each (I, J, K, L and A, B, C, D) are also the same. The basic cubo octahedron of the system is illustrated in Fig. 7-20 and the lattice, doubly expanded in all three dimensions, is illustrated in Fig. 7-21. Preceding and succeeding constant lightness planes are offset by one *j*, *g* unit. An illustrated description of the space lattice used was offered by Foss in 1978 (see Fig. 7-21).

A three-dimensional model of the system was manufactured by MacAdam. He mounted spheres, dipped in the formulated paints, in cubo octahedral configuration as shown in Fig. 2-51. This figure, as well as Fig. 7-20, illustrates the existence of seven cleavage planes that allow bisection of the color solid in various directions. The cleavage planes are formed by the following points in the figure:

Plane 1	E, F, G, H (constant lightness plane)
Plane 2	B, F, I, K, H, D
Plane 3	A, F, I, L, H, C
Plane 4	I, J, G, D, C, E
Plane 5	K, L, G, B, A, E

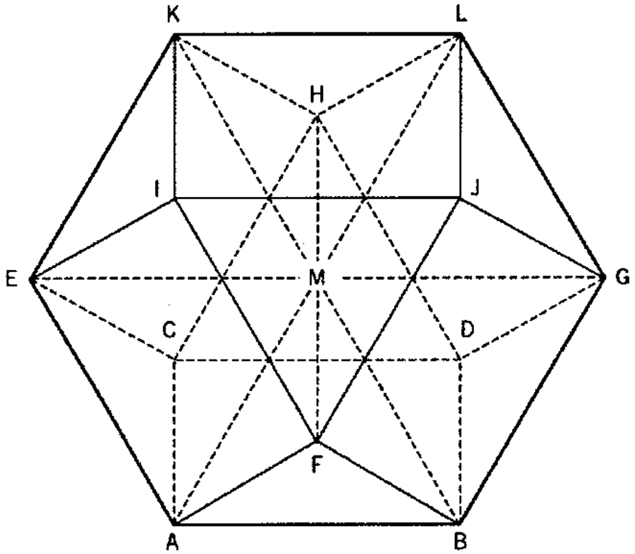

Fig. 7-20 *Cubo octahedral arrangement of twelve colors equally distant from central color M. Colors I, J, K, and L represent the square forming the square grid pattern of the OSA-UCS system at constant lightness. Compare with Figs. 2-49 and 2-50.*

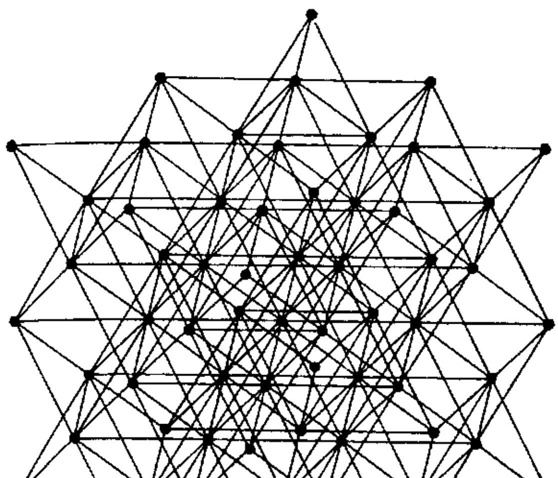

Fig. 7-21 *Basic cubo octahedral unit lattice doubly expanded in all three dimensions. From Foss (1978).*

Plane 6 I, A, D, L
Plane 7 J, B, C, K

In 1974 MacAdam stated: "The regular-rhombohedral system of color sampling adopted by the Optical Society Committee on Uniform Color Scales provides the maximum possible number and variety of uniform color scales and exhibits the maximum possible variety of relationships among colors. The committee hopes that artists and designers will find it useful in devising new and beautiful arrangements of colors."

An identification system based on three numbers was devised to designate each color. The letter j (for the French *jaune*, yellow) roughly indicates yellowness-blueness, the letter g approximately greenness-redness, and the letter L lightness. For the samples of the atlas j ranges from –6 (blue) to +12 (yellow), g from –10 (red) to +6 (green), L from –7 (dark) to +5 (light). Simple mathematical relationships connect the colors of each cleavage plane. In studying systematic color scales, the committee noticed the paucity of near neutral samples and decided to add a series of such samples at half steps, centered on $L = 0$ (the pastel set). The 134 samples of that set range from $L = -1.5$ to $L = 1.5$.

The Optical Society published in 1977 an atlas containing a total of 558 glossy color chips (424 of the regular and 134 of the pastel set), representing the regular rhombohedral system. Colorimetric specifications of the aim colors in terms of CIE chromaticity coordinates and luminous reflectance for the 10° observer and illuminant D65 have been provided by MacAdam (see also Wyszecki and Stiles, 1982).

A detailed description of the regular rhombohedral structure of the OSA-UCS system is found in Agoston (1987). A standard practice for using the system has been issued as ASTM procedure E1360. A software package, Color Cleaver®, is available that displays approximate OSA-UCS scales on a color monitor (Luke, 2001).

A Revised OSA-UCS

In 1990 MacAdam published a revision of OSA-UCS based on 2000 judgments by two young color normal observers. A major advantage claimed by MacAdam for the new observations is that for the first time samples of all twelve lightness planes were evaluated by the same observers. As a result of regression calculations he proposed redefined R and B values as well as redefined j and g values:

$$\begin{aligned} R &= 0.9285X + 0.3251Y - 0.1915Z, \\ B &= -0.2032X + 0.60Y + 0.5523Z, \\ g &= C(12.7R^{1/3} + 19G^{1/3} - 6.3B^{1/3}), \\ j &= C(-1.3R^{1/3} + 17G^{1/3} - 15.7B^{1/3}). \end{aligned} \tag{7-2}$$

These changed values amount to a significant revision. MacAdam also calculated revised aim colors for a regular rhombohedral system based on the revised coordinates.[5] A limited number of corresponding samples were prepared in Denmark by Ransing. However, in a handwritten letter dated March 22, 1995, MacAdam stated: "Incidentally, I have found some errors in that (1990) JOSA paper, and withdraw it entirely." (MacAdam, 1995) An extensive visual confirmation of the OSA-UCS scales is missing to date (but see Indow, 2001).

Comparisons of the Munsell Renotations with OSA-UCS have been made by Wyszecki (1954), Nickerson (e.g., 1978), and Agoston (1987).

How Uniform Is OSA-UCS?

Disregarding hue superimportance in the formula resulted in reduced correlation and, presumably, perceptual nonuniformity of the differences between the samples. In the late 1980s an Inter-Society Color Council Project Committee (44) performed scaling near the achromatic point of the OSA-UCS scales. They found the first steps from gray in the four axis directions of the even numbered lightness levels to be too large compared to more chromatic steps, perhaps indicative of a small chromatic crispening effect. The results of the committee have not been published, and it has been dissolved.

Recently Indow has begun to psychologically measure OSA-UCS using comparison against a Munsell value step. Preliminary results (Indow, 2001) indicate a surprising level of disagreement between the committee results and those of Indow. The disagreement appears to be random in nature. Visual differences along constant j and g lines in the $L = 0$ constant lightness plane vary from 0.63 to 1.55, a factor of nearly 2.5. The coefficient of variation of all of Indow's judgments against the system is 23%. The first steps from gray were found to be larger in the red and blue directions as compared to the green and yellow directions, a result not in agreement with that by Kuehni (2000c).

As already Reilly had found, considerable improvement of fit over that achieved by the committee's formula is possible by considering hue superimportance. Considerable reduction in the RMS error (when compared to visual data) is obtained by separately weighting by quadrant the hue and chroma differences. They are calculated for differences between sample pairs of applying CIELAB methodology to the OSA-UCS total differences. Chroma and hue differences were calculated assuming a euclidean space. The optimization was limited to the 104 differences involving the original 43 tiles. Optimal results by the method described were obtained when multiplying in quadrants 1–3 chroma differences with the factor 0.6 and hue differences with the factor 1.3. In quadrant 4 the factors 1.3 for chroma differences and 1.8 for hue differences proved optimal. The higher values but smaller ratio for quadrant 4 (greenish-bluish colors) indicate that here the visual differences between sample pairs were seen as relatively larger than in the other three quadrants, for reasons that are not obvious. The factors in quadrants 1–3 indicate a superhue weight of 2.2 (close to the one obtained by Reilly, mentioned earlier). The resulting average total color difference was nearly identical to the committee's value for these data. For the reduced data set (104 differences) the committee's RMS error is 20.2%, with a result of 12.7% after the described optimization. The correlation coefficient is improved from a value of 0.45 to 0.81. The results indicate that due to superimportance of hue the unit chromatic difference contours in the OSA-UCS basis data in the *j*, *g* diagram are also elongated in a radial direction, in agreement with the Munsell and small color difference data.

More exactly the ratio of the multiplication factors in quadrants 1–3 is 2.17, comparable to the ratio of 2.0 for Munsell colors at chroma 5 (2.8 at the JND level). In quadrant 4 it is 1.38. Colors falling on diagonals at 45 and 135° are chroma differences only. Colors such as *j*4, *g*0 and *j*0, *g*4 are essentially hue differences from *j*2, *g*2, a color on the diagonal. If hue superimportance has been suppressed in the physical system, one would expect the essentially hue differences to be perceptually larger than the chroma differences. Informal evaluations confirm this. A formal experiment is required. The situation implies that in the final system the visual distances along diagonals in a square anchored at the neutral point are not identical as they should be in a uniform system.

As a result we find that the apparent paradox of circular unit chromatic contours in OSA-UCS compared to the elongated unit contours in the Munsell system and in small color difference data is due to the suppression of hue superimportance in OSA-UCS. In reality the visual data in all three cases are in general agreement. The suppression has also resulted in unequal visual distances along diagonal lines in the *j*, *g* diagram. As a result of these nonuniformities the major value of OSA-UCS should today perhaps be seen in its various types of more or less uniform scales and their aesthetics.

OSA-UCS Psychological Space and Psychophysical Representation

The form of the OSA-UCS psychological space is that of a cube. The chromatic plane is defined by a regular grid of squares. While lightness is an explicit attribute, hue and hue difference is not. Chroma is only explicitly defined along the two major axes and the diagonals. All other steps in the chromatic plane are varying sums of hue and chroma differences. As mentioned before, unlike Munsell, the OSA-UCS system is defined against a specified surround of $Y = 30$ and constant lightness of chromatic samples does not imply constant luminous reflectance because the latter has been adjusted to reflect the Helmholtz-Kohlrausch effect. The locations of unique hues in OSA-UCS as shown in Table 4-1 indicate that this system is considerably different from a Hering system in terms of implied hue spacing.

Plots of X against Y values (Fig. 7-22*a* and *b*) of colors along the axis where $Z = 0$ and Z against Y where $X = 0$ reveal a picture similar to that of Fig. 7-11*a* and *b*. However, the spacing is more uniform and continuous throughout

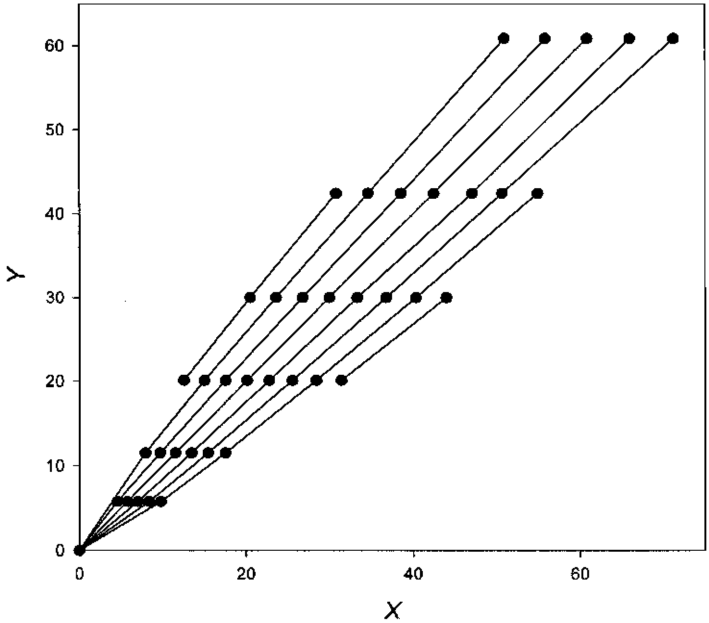

Fig. 7-22a *OSA-UCS colors falling on the g axis at six levels of lightness* L *in the* X, Y *diagram. Achromatic colors fall on the diagonal, 10° observer and illuminant D65. Colors of constant chroma at different value levels are connected by lines. Compare with Fig. 7-11*a.

the range as one would expect from partitioning of the scale by a formula. Here the first steps from gray were found to be in good agreement with the average judgment of 35 observers (Kuehni, 2000b). As mentioned earlier, the optimized linearizing powers are 0.84 for the green colors and 0.70 for the red colors. They are 0.58 for the yellow colors and 0.33 for the blue colors. The average increments in X and Z have the same ratio of 1:2.4 in OSA-UCS and Munsell, but the average increment is 30% larger in OSA-UCS than in Munsell. Figure 7-23 illustrates the Weber fractions for Z (comparable to Fig. 7-12) at six levels of lightness for colors on the j axis. They have a greater regularity than those for the Munsell system for reasons mentioned.

7.3 THE SWEDISH NATURAL COLOR SYSTEM (NCS)

The designation "natural color system" has been used by Hering (*Das natürliche Farbsystem*; Hering, 1905). To quote Hering: "For a systematic grouping of colors the only thing that matters is *color* itself. Neither the qualitative (frequency) nor quantitative (amplitude) physical properties of the radiations are relevant."[6] Thus Hering developed a system on perceptual basis only. He postulated two achromatic percepts white and black and their ratio *W/B* representing proportions. From this follows the expression for whiteness

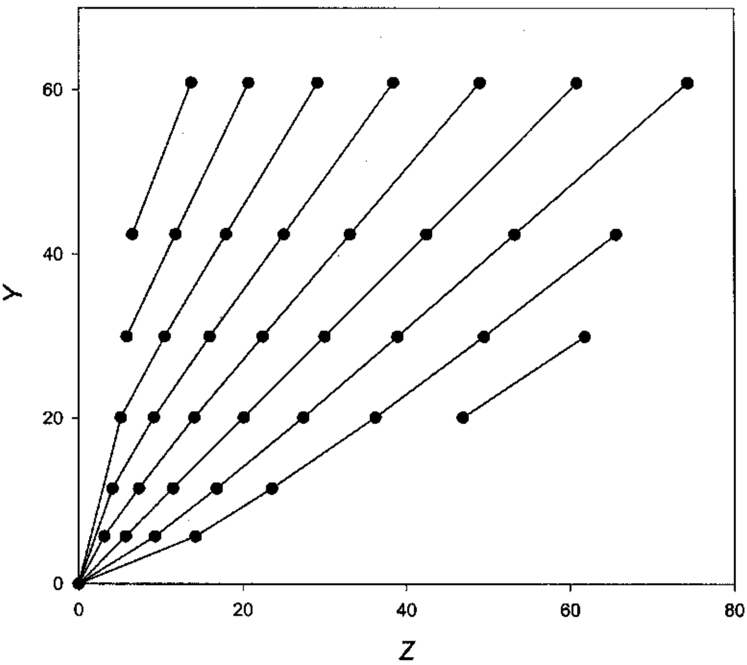

Fig. 7-22b *OSA-UCS colors falling on the* j *axis at six levels of lightness* L *in the* Z, Y *diagram. Achromatic colors fall on the diagonal, 10° observer and illuminant D65. Colors of constant chroma at different value levels are connected by lines. Compare with Fig. 7-11*b.

$H = W/(W + B)$. Hering then described the development of a perceptually equally spaced gray scale, based on the degree of similarity of a given step to white and black. Most chromatic object colors, according to Hering, appear veiled by the presence of whiteness, grayness, or blackness. "Chromatic colors that do not obviously show such veiling I shall call unmasked chromatic colors. . . ." Unmasked and veiled chromatic colors can be ordered according to hue in a color circle. Hering defined four unique hues (*Urfarben*) and placed them in such a manner on the hue circle that they divide it into its four quadrants. Nearly one-half of this circle contains yellowish colors, nearly the other bluish, and so for greenish and reddish colors. The colors in a quadrant can then be defined by the relative amounts of the two adjacent unique hues in a way similar to that described for achromatic colors. Hering placed the unmasked (or "full," *Vollfarbe*) color, black, and white at the corners of an equilateral triangle into which all veiled colors of the hue of the unmasked color can be systematically arranged.

Hering believed that the clarity of chromatic colors could not be determined exactly; it can only be said of two colors which one is less veiled. "In my view, every color that we actually see is more or less veiled. . . ." Any object color perception can be described by its chromatic and achromatic compo-

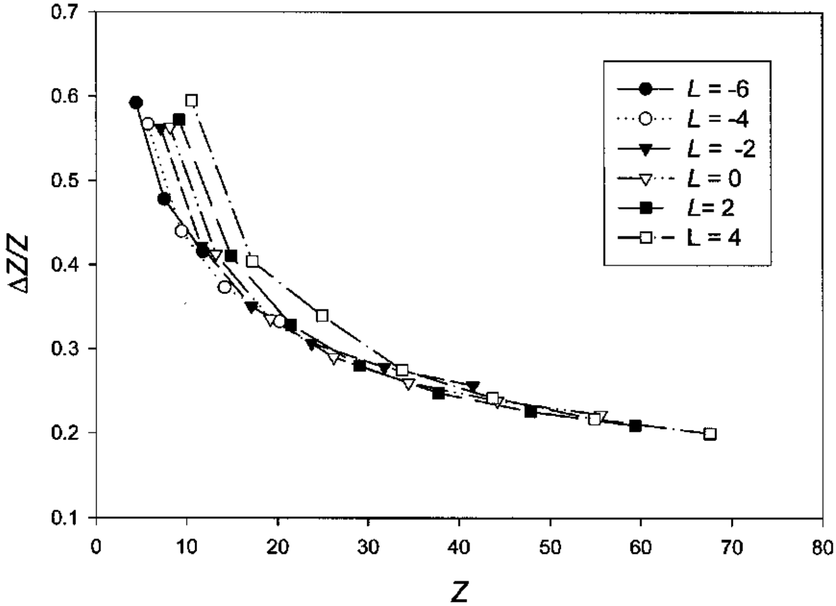

Fig. 7-23 *Weber fractions of* Z *for OSA-UCS colors falling on the* j *axis, at six levels of lightness* L*, 10° observer and equal energy illuminant. Compare with Fig. 7-12.*

nents: "It can be said that in each clearly veiled chromatic color both a chromatic and a black-white component can be distinguished. . . ." Regarding lightness/brightness of chromatic colors Hering said: "It is not such a simple matter for chromatic colors, whose brightness or darkness is determined not only by their black-white components, but also in part by their chromatic components. . . . I have . . . ascribed an *intrinsic brightness* to yellow and red and an *intrinsic darkness* to blue and green." Hering's equilateral constant hue triangle therefore does not express anything about lightness or darkness of its colors but only about the degree of veiling of its full color with white and/or black.

As discussed in Chapter 2, Ostwald departed from Hering in attempting a psychophysical definition while maintaining the geometrical form. Restricting himself to colors that could be achieved with colorants, his full colors of necessity fell short of Hering's full colors. The form of his color solid is based on an arrangement of Hering type constant hue triangles in a hue circle, resulting in a double cone solid. But his hue circle is not based on unique hues but on yellow, red, and blue primaries.

In the same chapter mention is made of the efforts of two Swedish researchers, Johannson and Hesselgren, who tried to find a compromise between Hering's double cone and a color solid based in its third dimension on a lightness scale. Johansson accepted hue, saturation, and value or lightness as the three properties uniquely characterizing any color perception. He suggested adding to these clearness or brilliancy and efficiency or vividness. Hesselgren's color atlas of 1952 relied on his idea of subjective color standardization. Regularity of spacing in that atlas was not considered to be completely successful, and in 1964 the newly founded Swedish Color Center Foundation began work toward a revision of the Hesselgren atlas by making new psychophysical experiments. In 1966 Tonnquist reported on the determination of unique hues and a comparison between hue circles based on unique hues ("symmetrical") and those based on equality of perceived hue differences. At the time the plan was to revise the atlas to be in principal agreement with Johansson's version of a natural color system. Eventually, a decision was made to revert back to Hering's original ideas and develop the system accordingly (Hård et al., 1996).

In a pilot study forty subjects were divided into two groups, one of which assessed a series of color samples according to the Hering principles by reference to six samples representing the six elementary Hering colors. The other group assessed them without reference to samples but based on their internal concepts of the six elementary colors. While there were considerable absolute differences in the average percentages between the two sets of results, rank order showed a high level of correlation. The interobserver variability was found to be low and comparable for both groups. Encouraged by these results the Swedish Natural Color System (NCS) was developed on the basis of judgments without reference samples.

From information provided one can estimate that in the basic experiment about fifty observers visually assessed approximately 200 samples. Confidence intervals at the 95% level of the means of the percentage judgments were found to be less than 5 units on 100 unit scales each. Blackness was then compared to luminous reflectance, chromaticness to the euclidean distance from the neutral point in the CIE chromaticity diagram, and hue to the hue angle in the same diagram. From interpolation on these psychophysical scales some 900 samples were produced, and these were assessed in arrays by five to six trained observers for smoothing purposes ("beauty test for acceptance").[7]

The structure of the system is illustrated schematically in Fig. 7-24. It consists of a double cone, formed in the atlas by forty equilateral constant hue triangles. A gray scale forms the centerline connecting the two apices.

Fitting of Psychophysical Scales

A hyperbolic formula was fitted by least square method to the visually established gray scale and was found to be in agreement with the Adams-Cobb formula for a surround of $Y = 56$: $w = Y(56 + 100)/(Y + 56)$. This was found to be in reasonable agreement with the luminous reflectance of the light booth interior used in the judgments ($Y = 54$), even though the luminous reflectance of the immediate surround had $Y = 78$.

Other relationships to psychophysical scales were found to be much less direct. Lines connecting samples with constant luminous reflectance were

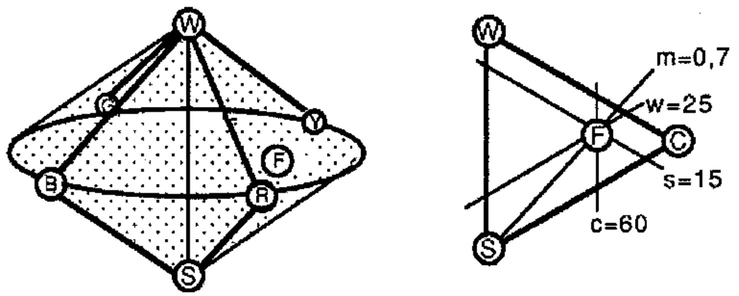

Fig. 7-24 *Schematic views of NCS.* Left*: double cone with circle of full colors.* W*: white;* S*: black;* F*: location of a given color in the double cone.* Right*: Constant hue triangle with full color C. The location of color F is determined by its blackness* s *and chromaticness* c*. From the two values whiteness* w *can be derived. From Hård et al. (1996).*

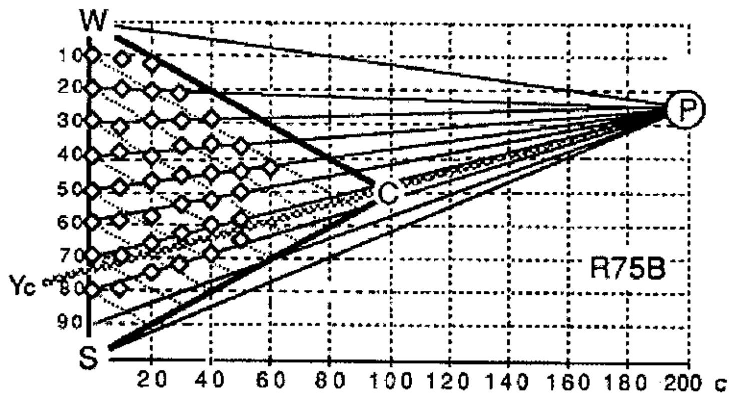

Fig. 7-25 *Lines connecting colors of constant luminous reflectance for NCS hue R75B.* Y_C *denotes the intrinsic blackness of full color C. From Hård et al. (1996).*

plotted into constant hue NCS triangles and found to approximately intersect at a point outside the triangle (Fig. 7-25). The position of this intersection point varies widely by hue. Dominant wavelength of constant hue colors, as one would expect, varies for most colors as a function of chromaticness and lightness.

In the CIE chromaticity diagram or the a^*, b^* diagram NCS constant hue lines are not straight, and constant chromaticness lines do not form circles, pronouncedly so at higher chromaticness (Fig. 7-26). One of the reasons is Hering's arbitrary decision to value chromaticness of all full colors identically at 100. In terms of chroma they vary significantly. Meaningful hue angle differences between hue steps, such as presented in Fig. 5-25 for the Newhall data set, cannot be calculated because of the very considerable variation in lightness of the full colors. The work of Billmeyer and Bencuya (1987) indicate the considerable difference in apparent hue spacing of the Munsell Renotations

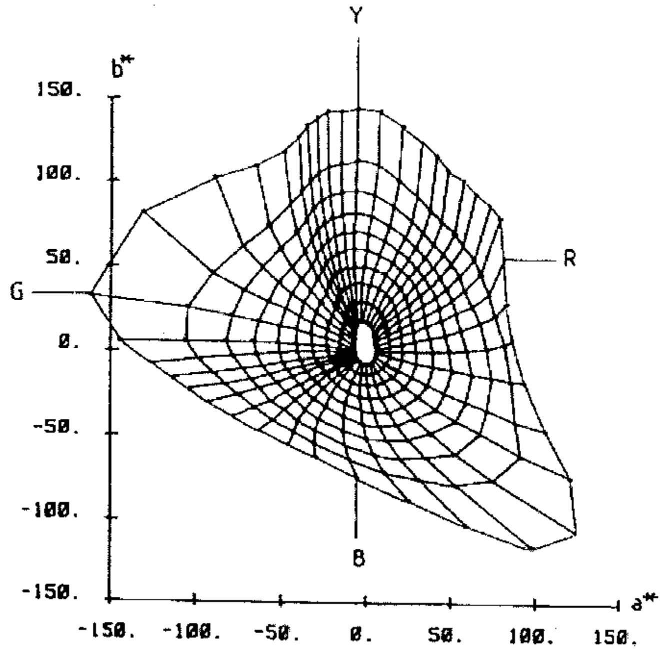

Fig. 7-26 NCS colors of constant hue (radial lines) and constant chromaticness (ovoids) in the CIELAB a*, b* *diagram. Capital letters indicate the four NCS unique hues. From Derefeldt and Hedin (1987).*

compared to NCS. As discussed in Chapter 5, depending on what is true constant chroma, the Renotations may contain some hue-chroma conflation. In the case of NCS where constant hue steps at constant chromaticness involve changes in hue, chroma, and lightness, hue steps likely involve a considerable degree of conflation. The disagreement in apparent hue angle differences is therefore not surprising. Indow has recently also begun to investigate the psychological spacing of NCS (Indow, 2001). Of interest is the visual judgment of the hue circle at constant blackness and chromaticness. A complete circle was visually judged at $s = 20$ and $c = 60$ and a partial circle at $s = 10$ and $c = 70$. Based on summation of differences the segment angles in the inner circle between the four unique hues of the system are R-Y 93°, Y-G 85°, G-B 82°, and B-R 100°, These figures deviate considerably from those of Table 4-1.

In a manner comparable to that shown above for the Munsell Renotations and OSA-UCS, the colors falling near the axes in the *X*, *Y*, *Z* space are shown in Fig. 7-27*a* and *b*. These figures demonstrate the significant difference between attempted uniform color solids and NCS. While the systematic arrangement of the samples is apparent it is of an entirely different nature than that of roughly uniform solids. Developers of NCS have written computer

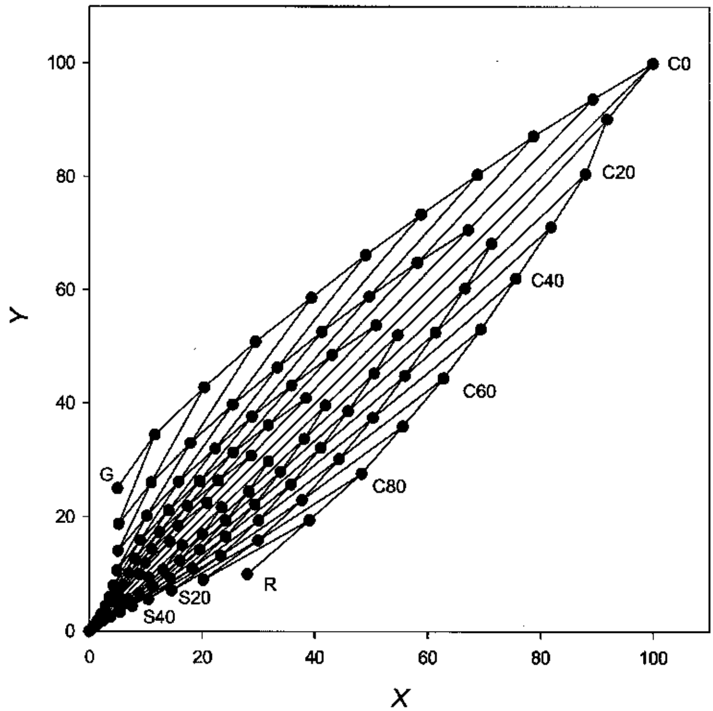

Fig. 7-27a NCS colors falling closest to the a opponent axis in the X, Y *diagram. Achromatic colors fall on the diagonal. Lines converging on the diagram origin connect colors of constant NCS chromaticness, curved lines connect colors of constant blackness, 2° observer and equal energy illuminant. Compare with Figs.7-11*a *and 7-22*a.

software that converts, by iterative methods CIE colorimetric values, into NCS values, and vice versa.

NCS Color Terminology and Atlas

Around the 40-step hue circle the hues (other than the unique hues) are identified in terms of their two constituting unique hues, for example, R70B, with the meaning of a hue constituted of 30 parts redness and 70 parts blueness. For veiled colors, according to Hering, the sum of the components of one or two unique hues, whiteness and blackness, is always 100. Chromaticness c is expressed as the percentage of chromatic components in the total color. The full specification of an NCS color is expressed as in the following example: 4030-R70B, indicating a color of blackness $s = 40$, chromaticness $c = 30$, and hue as defined above. The system and applications have been described by Hård and Sivik (1981) and by Hård et al. (1996a, b).

The 1995 edition of the atlas contains 1750 color chips of 13 × 15 mm size arranged on forty pages (see Fig. 2-53). It is available in a matte and a glossy

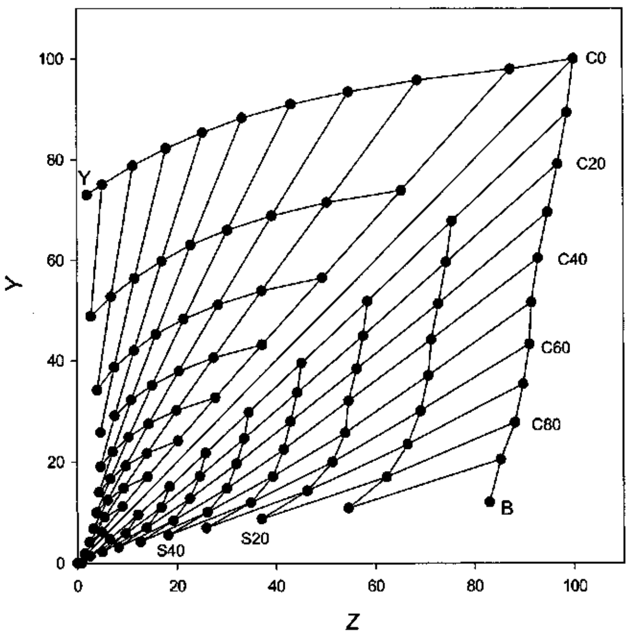

Fig. 7-27b *NCS colors falling closest to the* b *opponent axis in the* Z, Y *diagram. Achromatic colors fall on the diagonal. Lines converging on the diagram origin connect colors of constant NCS chromaticness, curved lines connect colors of constant blackness, 2° observer and equal energy illuminant. Compare with Figs. 7-11*b *and 7-22*b.

version. Swedish Standard SS 01 91 03 contains the aim color specifications of the atlas and many interpolated and extrapolated colors (16,800) in terms of CIE tristimulus values and chromaticity coordinates for the CIE 2° observer and illuminant C.

NCS System and NCS Atlas

The NCS system in its essence represents Hering's idea of describing any object color perception by its chromatic content and veiling with blackness and/or whiteness. To this idea the developers of NCS added a color identification methodology and the claim that any observer with normal color vision can assess the chromatic, black and white contents of any object color with good accuracy.

The atlas represents a curiously dissonant position. On the one hand, a claim for the system is that it is independent of a specific reference frame and that it can be used successfully in any kind of environmental situation. The user, it is claimed, can make quite accurate judgments of the content of the six primary color experiences of any perceived color in any situation. On the other hand, colorimetric specification and quality control was required to meaningfully embody the system in the atlas.

The NCS atlas is a material example of the NCS system instantiated for a particular surround and lighting condition: achromatic surround of $Y = 56$ and CIE illuminant C, with the samples of a size to be, at normal viewing distance, in agreement with the CIE 2° standard observer. Strictly speaking, for other situations the atlas is less or not valid.

7.4 THE "FRAGILITY" OF COLOR ATLASES

Color atlases, such as those described above are fragile in a metaphorical sense as well as in reality. The variability of observer responses to color stimuli and the fact that less than ideal colorants are used to color atlas chips make color atlases fragile in a metaphorical sense. The three described atlases all have been prepared with the help of colorimetric tools. In the case of the Munsell system the Renotations are defined in terms of colorimetric data from which they can be instantiated by matching tristimulus values. The aim values have been arrived at by plotting, smoothing, and interpolating results of visual evaluations. In case of the OSA-UCS atlas a formula has been fitted to a set of visual data, and that formula has been used to tile the space according to the principle of interlocking cubo octahedra. The resulting L, j, g values have been converted back to tristimulus values that are the aim points for the generation of atlas chips. A similar process of defining colors has taken place in generating the NCS chips. A quality issue relatively easily definable and controllable is that of the agreement between aim color and atlas color in terms of colorimetric coordinates.

For more recent atlas editions an aim has been to select pigments that not only are color fast but that result in colorations reasonably color constant when the atlas is viewed in different phases of daylight or artificial daylight sources. None of the three systems makes any but the most general claims in this respect. The available selection of suitable pigments is not such that a significant degree of demonstrated color constancy under different light sources is possible. Atlases have been formulated for CIE daylight C or D65. There are no artificial light sources that closely match these phases in spectral power distribution. Artificial daylight sources are today usually based on fluorescent lamps, and while they match the correlated color temperature of a particular daylight phase, their spectral power distributions are often significantly different. So-called triband lamps (CIE illuminant F11) are particularly different. As a result the appearance of the chips can change significantly, and the original goal of uniformity or regularity of spacing is no longer met or met less well.

The issue of surrounds has been discussed earlier, but a color atlas is valid in its appearance strictly only for the surround color for which it has been designed. Distortions in scaling take place if the surround is different in lightness or chromaticity from the design surround. Distortions due to surround can be relatively large because of crispening effects.

Since a numerical standard observer has been used in the design of atlases, individuals with normal color vision viewing an atlas experience smaller or greater distortions when viewing it, based on the difference between their color vision apparatus and that implied for the standard observer, and likely due to additional reasons. An idea of the magnitude of the changes in experience can be gleaned from the range of colors selected as unique hues by a group of observers (see Chapter 1). In addition observers have varying perceptions of equality of lightness, chroma, and hue steps to a degree that is unknown. Different assessments of constant chroma circles by observer groups in past extensive visual experiments, and different assessments of the number of constant size hue steps between unique hues, as discussed in Chapters 4 and 5, give an indication of the magnitude of these problems.

Aside from these conceptual fragilities there are also material fragilities. Of particular importance here is the resistance of pigments to degradations of various kind. Pigments, binders, and other materials are selected to make modern atlases long lasting. However, much depends on the kinds and lengths of exposures atlases suffer in use.

In this chapter three major color order systems have been compared, two attempts at a uniform color solid and the third a Hering type color solid. The considerable differences between the former two and the latter are evident from views of the distribution of samples in the X, Y and Z, Y planes at the system axes. Hue superimportance is implied in the Munsell system (as a result of the unequal magnitude of hue and chroma scale intervals). It is nonuniform in its euclidean form and non-euclidean when uniform. The system considers neither the Helmholtz-Kohlrausch effect nor the surround lightness. The OSA-UCS system, not arranged according to hue and chroma attributes (in fact, not directly expressive of meaningful chromatic attributes), does not in its final form indicate hue superimportance. However, analysis of the basis data clearly shows the presence of this effect. Hue superimportance was suppressed in the final formula used to tile color space according to this system to make the space euclidean. As a result the system is not uniform. The suppression explains the apparent difference in unit difference chromatic contours between the Munsell system and suprathreshold small color difference data, on the one hand (of generally oval shape), and OSA-UCS, on the other (circular). The circular unit contour is not in agreement with the perceptual facts of the OSA-UCS basis data. OSA-UCS, however, is built under consideration of the Helmholtz-Kohlrausch effect and of a specific achromatic surround. The NCS solid has been developed based on Hering's principles. Because the distances in the solid do not represent constant perceptual distances, there is no problem fitting the solid into a double cone. With minor changes it could be fitted into a sphere. We have arrived at an understanding that the three systems in effect represent regular color solids, none of them being able to make a strong claim for perceptual uniformity.